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The Search for Exoplanets: What Astronomers Know

Course Guidebook

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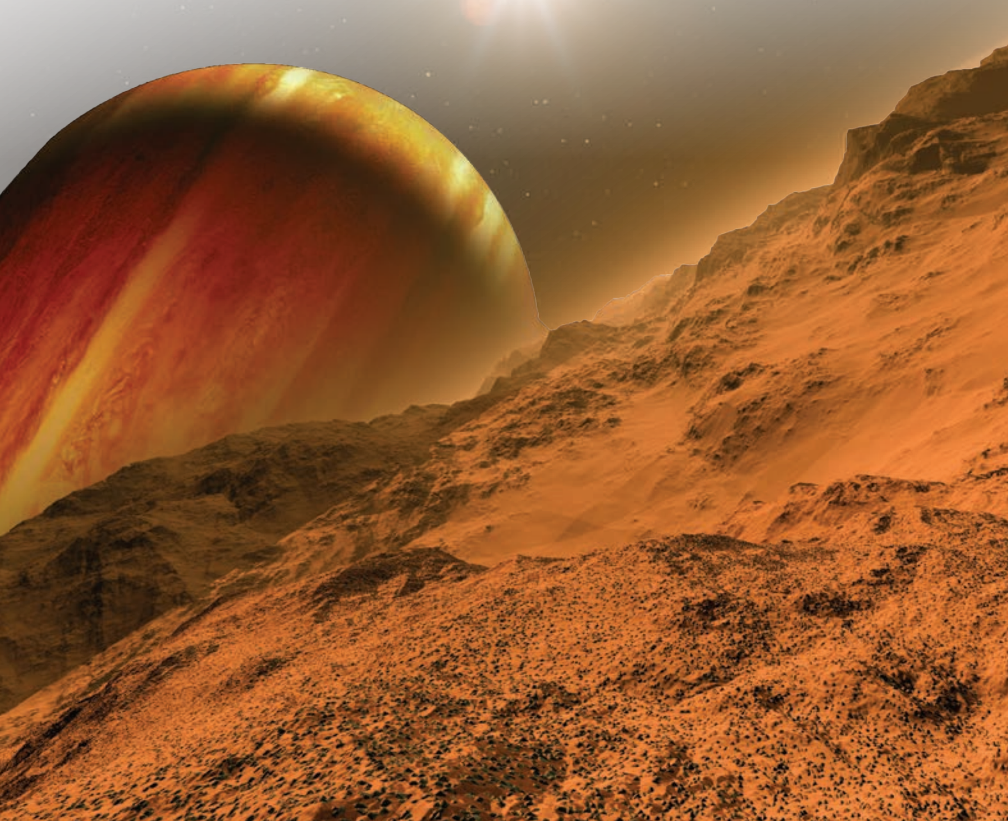

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Dr. Joshua N. Winn is an Associate Professor of Physics at the Massachusetts Institute of Technology (MIT), where he has been a member of the faculty since 2006. As an undergraduate student at MIT, he studied physics. After spending a year as a Fulbright Scholar at Cambridge University, he returned to MIT to pursue a doctorate. While in graduate school, Dr. Winn worked in medical physics, condensed-matter physics, and astrophysics and wrote for the science section of *The Economist*. After earning his Ph.D. in Physics from MIT, he held fellowships from the National Science Foundation and NASA at the Harvard-Smithsonian Center for Astrophysics.

Dr. Winn's research goals are to explore the properties of planets around other stars, understand how planets form and evolve, and make progress on the age-old question of whether there are other planets capable of supporting life. His research group uses optical and infrared telescopes to study exoplanetary systems, especially those in which the star and planet eclipse each other.

Dr. Winn was a member of the science team of NASA's Kepler mission, which had as its goal the detection of earthlike planets, and he is the Deputy Science Director of a future NASA mission called the Transiting Exoplanet Survey Satellite, scheduled for launch in 2017. He has authored or coauthored more than 100 scientific articles on the subject of exoplanetary science. Over the years, he and his research group have pursued topics in stellar astronomy, planetary dynamics, radio interferometry, gravitational lensing, and photonic bandgap materials.

At MIT, Dr. Winn teaches physics and astronomy and has won several awards for his dedication to his students, including the Buechner Faculty Teaching Prize in 2008 and the School of Science Prize for Excellence in Graduate Teaching in 2013.■

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The Search for Exoplanets: What Astronomers Know

Scope:

The last few decades have given birth to a new field of astronomy: the study of planets beyond our solar system, or exoplanets. Recent advances in technology have led to the discovery of thousands of these distant planets, and research data indicates that there must be countless others. The 24 lectures in this course provide a comprehensive and up-to-date introduction to this rapidly advancing field. Among the major topics are the comparison of exoplanets with the more familiar properties of the solar system, the basic physics of planet-finding techniques, the theory of planet formation, and the prospects for finding other planets very similar to Earth that might be inhabited by living creatures.

The course has 5 major parts. The first part, consisting of 3 lectures, will introduce the fundamental concepts that will recur throughout the course. The first lecture will include a brief tour of our own solar system, to establish the context for exoplanetary systems. Later in the course, you will meet some exoplanets that resemble some of the familiar planets from the solar system, as well as numerous exoplanets that are completely alien. The second and third lectures will be devoted to the difficult problem of how to detect exoplanets using telescope observations. This involves a marriage of physics, astronomy, and high technology. You will need to understand the basic principles of orbital dynamics, as determined by Newton's laws of motion and gravitation. The fourth lecture will examine the history of this subject and introduce you to some of the pioneers of planet searching. Given how recently this field emerged, many of the pioneers are still actively working today.

In the second part of the course, you will encounter the first big surprise of exoplanetary science: the existence of gas giant planets that orbit their stars much more closely than any planets orbit the Sun. In lectures 4 and 5, you will learn why this discovery was so surprising and examine the theoretical puzzles that these "misplaced giants" have raised. You also will explore some ideas for how they might be solved.

Then follows an in-depth investigation, over 8 lectures, of the intriguing properties of planets that have been found by virtue of planetary transits, the miniature eclipses that are produced when a planet blocks a small portion of the light of its own star. In this third part of the course, you will learn how it is possible to use transits to study exoplanet atmosphere and to measure an important aspect of a planetary system called spin-orbit alignment. You also will learn about the NASA Kepler mission, a space telescope specially built to find transiting planets. The Kepler mission propelled much of the recent progress in this field by finding thousands of new planets, including whole new categories of planets, such as compact multiplanet systems, circumbinary planets, and lava worlds.

The fourth part of the course is about the specific problem of finding planets that resemble the Earth around stars that resemble the Sun, as well as some variations on that theme. Finding exoplanets just like the Earth is an important part of the long-term quest to search for signs of life elsewhere in the universe. You also will learn about planets that occur around stars that are unlike the Sun, either because they are much smaller and fainter (lecture 16) or because they are older "red giant" stars (lecture 17). Many future initiatives are aiming to search all of the stars in our local neighborhood of the galaxy as thoroughly as possible for planets. In lecture 18, you will explore what is already known about the planets around our nearest neighbors.

The fifth and last part of the course is focused on the future. You will learn about a more exotic planet-finding technique called gravitational microlensing, which is based on Einstein's theory of relativity and might help locate thousands of new exoplanets using data from a future space telescope. Another planet-finding technique that is about to come of age is direct imaging, in which special optical instruments are used to reduce the glare from a bright star in an astronomical image and allow nearby planets to be spotted. After learning about these techniques, you will explore some of the plans for future telescopes and space missions to extend the search for exoplanets.

The final 2 lectures will take on the perennially fascinating but still highly speculative subject of life on exoplanets. You will learn about the 2 basic

approaches to this problem: the search for intelligent life through interstellar signaling and the search for life through the effects that living ecosystems produce on their planet's atmosphere. The course will conclude with a few specific predictions for new discoveries that might happen in the near term of 5 to 10 years from now. ■

Why Study Exoplanets?

Lecture 1

There are many reasons to study exoplanets, including exploration, the search for life, the rich physics problem of planet formation, and the technological challenge. In this course, you'll learn how astronomers search for planets around other stars and why it's so difficult. You'll get a complete briefing on this new field, which only got going in the 1990s. You'll learn about the new technologies that have allowed astronomers to make discoveries about exoplanets, what kinds of planets they've found, and how close they are to finding truly earthlike planets. You'll gain a solid physics-based understanding of this exciting realm of astronomy.

A Model of Our Solar System

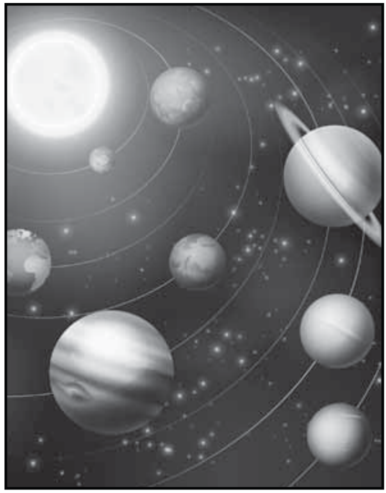
- Until the mid-1990s, the only planets we knew about were the ones that go around the Sun: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune—and Pluto. Pluto was once thought of as a planet, but we now understand it to belong to a different category from the others. It's one of many similar small objects that reside in the so-called Kuiper belt, a more distant version of the asteroid belt that exists between the orbits of Mars and Jupiter.

- A model of the solar system in which the sizes of the Sun and planets, and the distances between them, are in the correct proportions but are scaled down by a factor of 800 million brings things down to a more familiar, human scale.

- If we shrink the Sun—a giant, hot, glowing ball of hydrogen and helium—by a factor of 800 million, it has a diameter of 5 feet 8 inches.

- The innermost planet, Mercury, is an airless ball of rock and iron, with many craters—a lot like our familiar Moon. On the scale of our model, Mercury is the size of a pomegranate seed, about a quarter of an inch across.

- The next planet in our solar system is Venus. Venus is also a rocky planet, but unlike Mercury, Venus has a thick atmosphere of carbon dioxide, which blankets the surface and causes it to heat up to more than 850° Fahrenheit. It's an exaggerated version of the greenhouse effect we're concerned about on Earth. Venus also has clouds made of sulfuric acid. In our model, Venus is the size of a grape.



Our solar system consists of the Sun and 8 orbiting planets: Mars, Venus, Earth, Mercury, Jupiter, Saturn, Uranus, and Neptune.

- Earth and Venus are essentially twins when it comes to size and mass. They're both made mainly of rock and iron. For our model, we also can use a grape to represent Earth.

- Next is Mars, the red planet. Spacecraft and rovers have explored the surface and revealed landscapes of orange-brown rocks, mountains, and dried-up river valleys. It's another rocky planet, like Venus and Earth, though a bit smaller. In our scale model, Mars is the size of a cranberry.

- Continuing outward, the next planet is Jupiter, a behemoth made mainly of hydrogen and helium gas. The gases rotate around in distinct bands of latitude, occasionally getting swirled up into storms, most famously the Great Red Spot. To be on the same scale as our Sun and the inner 4 planets, Jupiter is nearly 7 inches across, the size of a cantaloupe. But in reality, there's no solid surface; Jupiter is a self-gravitating ball of gas.

- Saturn is another gas giant, but this one has a dazzling set of rings going around the planet. NASA's Cassini spacecraft orbits Saturn, delivering breathtaking views of those rings. In our scale model of the solar system, Saturn is a grapefruit.

- Finally, we have the planets Uranus and Neptune, which are sort of in between rocky and gaseous planets. They both have substantial amounts of solid material—rock and iron—but they also have lots of hydrogen and helium, as well as other lightweight molecules, such as water, methane, and ammonia. They don't have a solid surface, either. Instead, if you could travel inside them, you'd first find yourself surrounded by gas, and then as you descend and the pressure increases, the atmosphere would become more like a liquid, which gets denser and denser and gradually becomes solid.

- Uranus and Neptune are nearly twins, too, when it comes to size and mass. But instead of being a pair of grapes, like Earth and Venus, Uranus and Neptune are bigger. In our model, they're plums.

The Distances between Planets

- We need to space out the planets in our scale model so that the distances between them are on the same scale as their sizes. But the distances are vast. Even after shrinking down the sizes of their orbits by a factor of 800 million, we're going to need a lot of room.

- To help comprehend these distances, imagine that you're walking in Manhattan, in New York City, starting in Times Square, where a person-sized Sun resides. With all the fruit from our model in a backpack, imagine dropping off each planet at the appropriate distance.

- First, you walk along Broadway from 46th to 47th street, about 1 block north. That's where you drop a pomegranate seed—Mercury.

- Keep walking north, about 3/4 of a block, which is where you drop 1 of the 2 grapes, representing Venus.

- To get to Earth's orbit, keep walking until you've gone a total of just more than 2.5 blocks—so you're between 48th and 49th streets. At this point, you can set down the grape representing Earth. When you look back at the Sun in Times Square, it looks small; you can cover it up with a dime when you hold out a dime at arm's length. That's the same size the actual Sun looks to us in our sky.

- Keep walking north until you've gone a total of 4 blocks, where you set down the cranberry, Mars.

- To reach the distance of Jupiter's orbit and unload the cantaloupe, you need to walk almost 10 more blocks. You pass Carnegie Hall and walk into Central Park until you're more than 1 mile from where you started, where you can lay down the grapefruit, Saturn.

- But you're not even halfway done with your walk. Uranus and Neptune are much more remote. To get to Uranus's orbit, you need to walk another 1.1 miles, to the northern end of Central Park, where you drop 1 of the 2 plums.

- And Neptune might be Uranus's twin in size and mass, but it's not right next door. To get to Neptune, you need to leave Central Park and walk into Harlem, up to around 138th street, bringing your total distance up to 3.5 miles. That's where you drop the second plum.

- At this point, you're relieved that Pluto is not a planet—because if it were, you would have needed to walk another mile to get there, all the way to Yankee Stadium.

- In our scale model of the solar system, the entire Earth is the size of a grape, and the true distance from the Earth to the Sun of 93 million miles maps onto 600 feet. From this model, we get a sense of how spread out the solar system is, how small the planets are relative to the Sun, and how different the sizes of the planets are relative to each other—ranging from a pomegranate seed to a cantaloupe.

- One thing to keep in mind is that although we imagine that you were walking in a straight line and putting the planets along that line, in reality, the planets are all at different angles in their orbits, so they're usually in what look like random locations along the circles of their orbits. It takes a special coincidence for even 3 of them to line up, and you'd never see all 8 of them right along a straight line. Even to find all the planets in the same quadrant of the solar system—within 90° of each other—is rare, happening once every 120 years, on average.

The Study of Exoplanets

- There are 3 striking patterns in the solar system that are essential for the study of exoplanets.
  1. The planets go around the Sun in orbits that are very nearly circles. Mercury's orbit makes a small circle that's inside of Venus's larger circle, which is inside of Earth's circle, and so on. Interestingly, there's no law of physics that says that orbits must be circles. More generally, the laws of physics say that orbits are elliptical—they can range anywhere from circles to extremely elongated, narrow ovals—so it's remarkable that the orbits of all 8 planets in the solar system are nearly perfect circles.

  2. All the circles are all aligned with each other. They all lie flat in a single plane, which is also aligned with the equator of the Sun, so all the planets are revolving in the same way the Sun is rotating. The solar system seems like a tidy, well-aligned system.

  3. All the small planets—Mercury, Venus, Earth, Mars—are close to the Sun, and all the large planets—Jupiter, Saturn, Uranus, Neptune—are much farther away. This is unlikely to be a coincidence; it's almost as though the planets were neatly sorted. What was it that caused the small rocky planets to be so much closer than the giant gaseous planets?

- These 3 patterns have long been regarded as clues about the formation of the solar system and, by extension, the formation

of planets anywhere in the universe. One of the reasons we study exoplanets is that we want to see if the patterns that exist in the solar system—the circular, well-aligned orbits, with the small planets inside and the large planets outside—are universal, or just provincial.

- If you continued where you left off in your walk through Manhattan to reach an exoplanet, how far would you have to walk? In reality, where is the nearest exoplanet? There is evidence for a small rocky planet around one of the closest stars to the Sun, a star named Alpha Centauri B, which shines brightly in the southern hemisphere, in the constellation of Centaurus.

- Alpha Centauri B is very far away, even though it's the nearest exoplanet for which we currently have any evidence. In our scale model, you'd have to keep walking all the way across New York, and Connecticut, and way beyond; in fact, to get to Alpha Centauri, you'd end up walking 32,000 miles, a distance 30% longer than the circumference of the entire Earth.

- The distances between planets in our solar system might be large, but the distances to even the nearest stars are stupendously greater—so large that they're difficult to comprehend. Exoplanetary systems can have planets that are much closer to their stars than any of our planets are to the Sun. In our scale model, the Earth is a few city blocks from the Sun. But Alpha Centauri B's planet is much closer—only 24 feet away.

Suggested Reading

Chown, *Solar System*.

NASA Planetary Fact Sheets. http://nssdc.gsfc.nasa.gov/planetary/planetfact.html.

Rothery, McBride, and Gilmour, eds., *An Introduction to the Solar System*.

Questions to Consider

1. Which is more interesting: finding planets similar to Earth or finding planetary systems that are fundamentally different from the solar system?

2. Try to come up with your own version of a scale model of the solar system, based on familiar objects and places.

How to Find an Exoplanet

Lecture 2

In this lecture, you will be introduced to direct and indirect methods for exoplanet detection. In the direct method, we use a telescope to take a picture of a nearby star and search for small dots going around it. But almost all of our current knowledge about exoplanets has come from indirect methods, in which we use a telescope to monitor some property of the star, as precisely as we can, and then use the observed variations in that property, as well as our knowledge of physics, to infer the presence of planets.

Orbits and Centers of Mass

- Although we always say that Earth is orbiting around the Sun, the truth is that both the Earth and the Sun orbit around each other—they're both moving. For that, we can thank one of the most fundamental laws of physics, the conservation of momentum. If the planet is getting pulled in one direction, it is carrying momentum in that direction, and the law says that this has to be balanced by something carrying momentum in the opposite direction: The star moves in the opposite way.

- As a consequence, all the planets, and the Sun, are orbiting around the center of mass of the solar system, an imaginary point in space representing the average position of all the bodies in the system—an average weighted by mass.

- Because the Sun is by far the most massive thing in the solar system, the center of mass is near the center of the Sun. But it's not exactly at the center of the Sun. The biggest pull on the Sun is from Jupiter. The distance from the center of the Sun to the center of mass turns out to be comparable to the Sun's diameter, so the center of mass at any moment might be near the surface of the Sun, rather than its center.

- What this means is that if we want to detect a planet, but it's too faint to see, we can try to detect the orbital motion of the star

around the center of mass of its planetary system. If the star is circling around, and we don't see any other star nearby doing the pulling, then it's probably being pulled around by a planet. And if we keep tracking the star's motion precisely for many years, we can even figure out how many planets are there and how massive they are—the more massive, the larger the wobble.

Johannes Kepler (1571–1630) was a German astronomer whose laws of planetary motion are still important today.

Kepler's Laws of Planetary Motion

- Kepler's laws of planetary motion, named for Johannes Kepler, are 3 laws of physics that will be important throughout this course. Kepler's first law is that the shape of a planet's orbit is an ellipse. The orbits of solar system planets are nearly circles, but they're not exactly circles. They're slightly squashed circles, or ellipses. Interestingly, the ellipse is not centered on the Sun, or even the center of mass; rather, the center of mass is set off from the center of the ellipse, at a mathematical point known as the focus of the ellipse.

- We quantify how squashed ellipses are with a number called the eccentricity, which ranges from 0 to 1. An eccentricity of 0 means a perfect circle—the diameter is the same no matter which way you measure it. As the eccentricity approaches 1, the ellipse becomes flattened, with the diameter in one direction becoming much smaller than the perpendicular direction.

- The Earth's eccentricity is 0.017, so the Earth's orbit is nearly a perfect circle. But—because the orbit is not perfectly circular, and because the Sun is slightly off center—the Earth gets a little closer to the Sun in January than in June.

- Kepler's second law says that whenever a planet gets closer to the Sun, it speeds up, and when it gets farther away, it slows down. For planets like the Earth, on nearly circular orbits, this is a slight effect, but for some exoplanets, this can be a big deal.

- Kepler's third law establishes a connection between the size of a planet's orbit and the time it takes for the planet to go all the way around the orbit. The larger the orbit, the longer it takes to go around. The larger the orbit, the farther the planet has to travel, and the farther away the planet is from the star, the less it's getting pulled by the star's gravity, so it moves more slowly.

- Mathematically, Kepler's third law is written as $P^2 = a^3(4\pi^2/GM)$, where P is the orbital period, or the time it takes for a planet to complete a full orbit; a is the orbital distance, usually measured in astronomical units (AU); M is the mass of the star, usually measured relative to the Sun's mass, in solar masses; G is Newton's universal gravitational constant, which describes the strength of the gravitational force; and $4\pi^2$ is just a pure number. Thanks to this law, whenever we measure any 2 of P, a, and M, we can figure out the third one.

The Astrometric Technique

- With a telescope, we can gather a lot of light from a star and concentrate it onto a digital camera, which records an image. There are 3 basic measurement techniques for starlight: astrometry, spectroscopy, and photometry. Rather amazingly, all 3 of these methods offer the potential for detecting planets.
    1. Astrometry: We can measure which direction it's coming from. We can measure the star's exact position on the sky.

    2. Spectroscopy: We can measure the star's color. We take the starlight, and before we send it to the camera, we send it through a prism or through a diffraction grating—a piece of metal or glass with many closely spaced, parallel grooves etched in its surface. In either case, the effect is to spread out the starlight into a whole rainbow of colors. That's the star's

spectrum. Then, we send the spectrum to the digital camera, and we take a picture of it.

3. Photometry: We can measure the star's brightness. We take a series of pictures of the star, and in each one, we measure how much light actually fell onto the detector. We can check if the star is getting fainter or brighter or staying exactly the same.

- In the astrometric technique, we monitor the position of a star in the sky. The basic idea is that if the star has planets, then the star will be orbiting around the center of mass, and we might be able to detect that motion in a series of images.

- How much do we expect the star to wobble? Suppose that there are aliens in the Alpha Centauri system looking back at the Sun. They would see the Sun getting pulled around by all the planets, and the biggest effect would be from Jupiter. For simplicity, let's just pretend that Jupiter is the only planet. Then, from their perspective, the Sun would be a point of light that very slowly shifts in angle, back and forth, over the course of 12 years, the orbital period of Jupiter. The maximum size of that shift in position would be 3.7 milliarcseconds. (A milliarcsecond is a unit of angle, of position in the sky.) That's a tiny effect.

- When we use one of the best astronomical cameras, the Advanced Camera for Surveys on the Hubble Space Telescope, to make images of the sky, each individual pixel in the image represents 50 milliarcseconds. So, if the aliens from Alpha Centauri had a similar telescope, they'd need to measure the Sun's position to significantly better than 1/10 of an individual pixel.

- The mathematical formula for the size of the astrometric shift is $\theta = (a/d)(m/M)$, where θ is the maximum angular shift of the star; a is the size of the planet's orbit; d is the distance from the star to the Earth (d is much bigger than a); m is the planet's mass; and M is the star's mass. M is thousands of times bigger than the planet, so when

you divide them, you're going to get a number much smaller than 1. So, we're going to get a tiny answer for θ.

- It's also important to remember that Jupiter is the biggest planet. If we want to detect an earthlike planet, which is 300 times less massive than Jupiter, then θ is going to be 300 times smaller. Remember, too, that Alpha Centauri is the closest star system to the Earth. For any other star in the galaxy, d is going to be even bigger, maybe 100 times bigger, and because we are dividing by d, the shift is going to be that much smaller. A major limitation of the astrometric technique is that the effect gets smaller as the star gets farther away.

- Measuring the astrometric signal of an exoplanet is a daunting challenge. But if the aliens did manage to see the Sun wobbling around in place and measured that shift, θ, what would they learn?

- First, they'd measure how long it takes for the Sun to complete its wobble. That would tell them P, the orbital period. And let's say that the alien astronomers already knew the Sun's mass, M, and its distance, d, based on their other astronomical observations. That would allow them to use Kepler's third law: They'd insert P and M and calculate a, the orbital distance.

- Once they knew a, they'd be able to use the equation for the astrometric shift to figure out m, the planet's mass. Finally, they could measure the eccentricity of the Jupiter orbit by seeing how much the Sun's orbit speeds up and slows down over 12 years (Jupiter's orbital period), according to Kepler's second law.

- Even though the astrometric method reveals the planet's mass, period, orbital size, and eccentricity—which is not bad for an indirect technique—this method, so far, has not worked for planet detection. There have been many announcements of new planets that later turned out to be spurious. This method has not been fruitful because the signal is so tiny and because the Earth's atmosphere causes the positions of stars to appear to wander around randomly.

- The European Space Agency built a space telescope specifically devoted to astrometric measurements called Gaia, which was launched into space in December of 2013. Gaia's 5-year mission is to track the positions of about a billion stars with unprecedented precision. This will be good for many different reasons, not just detecting planets; its main job is to create the most detailed 3-dimensional map of the galaxy that has ever been made.

- While Gaia is tracking and measuring all those stars, it will sometimes see the additional wobbling motion due to the planets around those stars. According to our best forecasts, Gaia will find thousands of exoplanets around nearby stars. We'll learn their masses, periods, and the sizes and shapes of their orbits.

Suggested Reading

de Pater and Lissauer, *Planetary Sciences*, chap. 1.

ESA Science & Technology. http://sci.esa.int/gaia/.

Fleisch and Kregenow, *A Student's Guide to the Mathematics of Astronomy*, chaps. 2 and 4.

Perryman, *The Exoplanet Handbook*, chap. 3.

Ryden and Peterson, *Foundations of Astrophysics*, chap. 3.

Seager, ed., *Exoplanets*, chap. 7.

Questions to Consider

1. Try to use Kepler's third law to calculate the orbital period of Pluto, given that its orbital distance is about 40 AU. How many orbits has Pluto completed since its discovery in 1930?

2. Look up the Gaia mission online, and learn about its basic characteristics. What is its current status? Has it discovered any planets yet?

Doppler and Transit Planet-Finding Methods

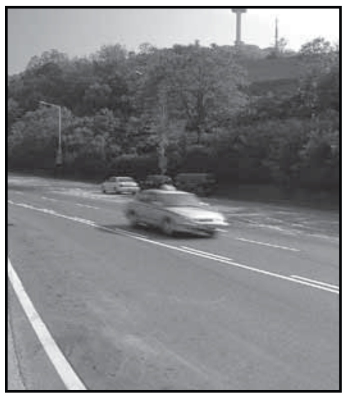
Lecture 3

Finding exoplanets isn't easy. So far, the astrometric technique has not been fruitful, because the signal is so tiny and because the Earth's atmosphere causes the positions of stars to appear to wander around randomly. In addition to the astrometric technique, there are 2 other indirect techniques for finding exoplanets: the spectroscopic and the photometric techniques. These 2 indirect techniques have delivered most of the known exoplanets, and they are the subject of this lecture.

Spectroscopy

- With the spectroscopic technique, we use a prism or a diffraction grating to spread out the starlight into the rainbow of its constituent colors. But what does the color of a star have to do with its motion around the center of mass? Understanding that is going to require some more physics. Specifically, we're going to need to understand a few things about light: the Doppler effect and spectral absorption lines.

- When a car speeds past you, the pitch is higher when it comes at you and lower when it goes away. That's the Doppler effect. It happens because the sound waves coming from the car are compressed when the car is speeding toward you, and shorter sound waves mean higher pitch. But when the car is speeding away, the waves get stretched out, and longer waves mean lower pitch.



The Doppler effect describes how a car's pitch is higher when it comes toward you and lower when it moves away from you.

- The same thing happens to any kind of wave that's emitted by a moving object. Importantly for astronomy, light is a wave. It is made of electromagnetic fields, which rise and fall in strength like the crests and troughs of an ocean wave. The spacing between these crests and troughs—the wavelength—determines the color of the light.

- For example, red light has a longer wavelength than blue light. When a light source is traveling toward us, the light waves are compressed, and shorter light waves mean a bluer color. But when it moves away, the light waves are stretched, and longer light waves mean a redder color.

- We never notice this in everyday life because the size of the effect—the percentage change in wavelength—depends on the speed of the moving object divided by the speed of light. The speed of light is very fast, and this means that the effect is too small to detect with our eyes.

- Fortunately, with decades of experience, astronomers have learned how to measure these Doppler shifts precisely. Part of what makes this possible is that the spectrum of a star is not just a continuous smear of color from red to orange to yellow to green to blue to purple. In addition to that rainbow, if you look closely, there are dark black bands, sort of like a bar code, imprinted on the rainbow. Those are spectral absorption lines.

- Those dark lines are there because each type of atom in the star—hydrogen, helium, iron, or carbon, for example—absorbs very specific colors of light. Hydrogen, for example, absorbs a dusky shade of red, with a wavelength of 0.6563 millionths of a meter.

- Even though the light that comes up from a star's interior may be a continuous rainbow, the atoms in the star's outer layers punch out very specific colors, making those dark lines. And the dark lines are very convenient markers in the spectrum of a star—sharp features that we can track over time to see if the pattern is shifting back and forth in wavelength.

- The combination of the Doppler shift and spectral absorption lines allows us to track the motion of a star toward or away from us. It's useful for finding exoplanets because a planet causes its parent star to move. We can track the Doppler shift of a faraway star, and if we notice that the speed is changing in a manner consistent with an orbit, we can infer that there's at least one planet pulling it around.

- With the Doppler technique, you can only detect the motion toward or away from Earth, so if the planet's orbit happens to be oriented in such a way that the star never moves toward or away from Earth—if the plane of the orbit is exactly perpendicular to our line of sight—then the star will move in a small circle in the sky, and there will be no Doppler shift. That planet will be invisible to the Doppler technique.

- That kind of alignment is pretty special and unlikely to happen by chance. More often, the orbit will be tipped at some random angle, and there will be some Doppler shift. The problem is that if all you're measuring is the Doppler shift, you can't tell what that angle is. So, you can't tell the difference between a slow orbit that we happen to be viewing from the side, the orientation that produces the maximal Doppler shift, or a much faster orbit that is oriented nearly perpendicular to our line of sight so that only a small component of the motion produces a Doppler effect.

- The equation for the Doppler signal for the simplest case of a planet on a circular orbit is $RV = (2\pi a)/P(m/M)\sin I$, where RV is the star's radial velocity, the component of the star's velocity along the line of sight; a is the orbital distance of the planet (so $2\pi a$ is the orbital circumference, the total distance the planet goes during every orbit); P is its orbital period, or how long it takes to go around; m/M is the ratio of the planet's mass to the star's mass; and $\sin I$ selects out only the radial component of the star's motion (the "*I*" is for "inclination," or how inclined the planet's orbit is from our perspective).

- The Doppler technique, unlike the astrometric technique, only tells us the minimum possible mass of a planet; it cannot, by itself,

tell us the mass of the planet. This seemingly small detail plays a pivotal role in this field and its historical development.

Photometry

- Photometry is an astronomical technique that uses precise brightness measurements to detect exoplanets. To do this, we rely on eclipses. We search for those rare events when a planet's orbit happens to carry it directly in front of its parent star, as we see it from Earth.

- Even though we can't make an image of the disk of the star and actually see the planet's small shadow, in front of the star, we can tell it's there, because the star seems to drop in brightness by a little bit. That's because the planet blocks a small part of the star's light that would normally reach us.

- This happens every time the planet goes around the star, so when we see periodic dips in brightness, we can infer the presence of an orbiting planet, and we can even measure the planet's size, based on the amount of starlight that it blocks.

- In this context, when you have an eclipse of a star by a much smaller object, such as a planet, the event is called a transit. The planet "transits" across the face of its parent star, so this method is often referred to as the transit method.

- When Jupiter transits the Sun, it blocks 1% of the Sun's light. The Sun appears to get fainter by 1%, for about 12 hours. Then, it goes back to full strength again. That might sound small, but it's enormous compared to the astrometric signal (measured in milliarcseconds) and the Doppler signal (measuring a wavelength shift of 1.0×10^{-8}). You can measure a 1% change with modest equipment—with a telescope small enough to hold in your hands and a decent digital camera.

- With the transit technique, we are trying to detect the apparent drop in brightness of a star when a planet is blocking some of its light. The fraction of starlight that is blocked during a transit is $dI/I = (r/R)^2$,

where r is the planet's radius and R is the star's radius. It's a 1% effect if a planet as big as Jupiter goes in front of a star like the Sun.

- There are a few things that make the photometric, or transit, technique challenging: the low probability that the orbit will be oriented just the right way and the brief duration of the eclipses. The vast majority of exoplanets do not transit their stars, so we'll never find them with the transit technique. And even when eclipses do happen, they're very brief.

- Also, the signal of a Jupiter-sized planet might be 1%, but smaller planets produce smaller signals. The fractional drop in brightness is equal to the area of the planet's shadow divided by the area of the whole stellar disk, which is equal to the square of the ratio between the planet's diameter and the stellar diameter. When Earth transits the Sun, the Sun's brightness drops by only 84 parts per million—and that you cannot detect with a backyard telescope.

- The twinkling effect of the Earth's atmosphere corrupts our brightness measurements, just as it corrupts our astrometric measurements. The noise is at the level of a few hundred parts per million, which interferes with any attempt to detect the transit of an earthlike planet. The solution is to use a space telescope. This not only improves the precision of brightness measurements but also makes it easier to monitor stars continuously without getting interrupted by daytime or bad weather.

The Path to Finding Exoplanets

- All 3 of these methods—astrometry, spectroscopy, and photometry—involve the physics of orbital motion, and they all present some very serious challenges.

- The astrometric technique has not been productive. The atmosphere corrupts the measurements, the signals are too small, and the signal size decreases with distance from the Earth. There aren't that many stars close enough to Earth for this to be realistic right now, but the Gaia mission should soon change that.

- The Doppler technique has been a real powerhouse. It's what got this field going in the first place and provided most of the exoplanet discoveries for the first decade of the field, from the mid-1990s until the early to mid-2000s.

- The transit technique also has turned out to be very powerful but took longer to reach maturity. In the early 2000s, astronomers started building automated telescopes to keep hundreds of thousands of stars under continuous surveillance, looking for the tiny eclipses by planets. And they found them.

- A few years later, the European and American space agencies launched space telescopes to do the same kind of thing above the atmosphere, where the measurements can be done more precisely. Those experiments led to the discovery of thousands of exoplanets.

Suggested Reading

Fleisch and Kregenow, *A Student's Guide to the Mathematics of Astronomy*, chap. 3.

Questions to Consider

1. Think about the nearest exoplanetary systems to the solar system. Which would be the best way to find them: the transit technique or the Doppler technique? Why?

2. Try to use Kepler's third law to rewrite the Doppler equation as it was presented in the latter part of the lecture.

3. One challenge of indirect planet-finding techniques is the problem of false positives: phenomena other than exoplanets that can produce apparent variations in the position, Doppler shift, or brightness of a star. Can you think of any plausible phenomena that would produce false positives?

Pioneers of Planet Searching

Lecture 4

Exoplanetary science is a new science that really only got going in the mid-1990s. In a sense, the field has a longer history, going back to the 1940s. From the 1940s to the 1990s, dozens of exoplanet discoveries were reported—in some cases, by some of the world's most respected astronomers—and when they turned out to be erroneous, it cast doubt on the whole enterprise of exoplanet detection. As you will learn in this lecture, the history of how and when exoplanets were discovered is a history of false starts, followed by a remarkable true start.

The History of the Discovery of Exoplanets

- In the 1940s, the technology for astrometry became good enough to potentially detect planets. Astrometry is the measurement of the position of a star on the sky, and if the star has planets, its position will wobble back and forth. It's natural that astrometry was the first technique to seem to be poised to find exoplanets. It's the oldest technique in astronomy; it even predates the invention of the telescope.

- Of course, telescopes do help a lot. Also helpful was the development of astronomical photography in the late 19th century. Astronomers put cameras at the back ends of their telescopes, instead of looking through an eyepiece. That way they could make objective records of star fields on durable glass plates coated with photographic emulsions. Then, they could use microscopes and drafting equipment to make precise measurements of the positions of all the tiny dots in their images.

- By the mid-1940s, the precision of these measurements had improved to around 10 milliarcseconds, good enough to potentially detect giant planets on wide orbits. And a few astronomers noticed some stars that were wobbling, just as if they were being pulled around by planets.

- The most famous signal was found in the 1960s, from a star called Barnard's star. Peter van de Kamp started observing Barnard's star in 1938 from Swarthmore College's observatory in Pennsylvania. By the early 1960s, he had taken more than 2000 photographs of Barnard's star, enough to detect a wobble that seemed to imply a giant planet—60% more massive than Jupiter and orbiting every 24 years. By 1969, he concluded that there were actually 2 giant planets.

- The evidence seemed so compelling, and Van de Kamp was so respected, that the planets made it into all the textbooks for the next decade. Then, in 1973, George Gatewood announced that he had been gathering even better data with a different telescope and did not see the wobble. His data refuted van de Kamp's claims.

Using the Doppler Technique

- The next technique to mature was the Doppler technique, where we try to detect the motion of a star toward or away from the Earth. By the 1980s, a few astronomers realized that the technology was almost good enough to detect planets, and they began pursuing different ways to get an extra boost in precision.

- One of the most difficult problems to overcome is wavelength calibration. The goal is to obtain a series of spectra of a star—spaced out over days, months, or years—and look for tiny shifts in the wavelengths of the stellar absorption lines: Doppler shifts. The problem is that many other things besides the Doppler shift can produce tiny shifts in the locations of those lines in your image, making them appear to have changed in wavelength.

- The solution is to have a good wavelength calibration—some kind of markers in the spectrum that tell you the correct wavelength at each position. Different groups do this in different ways.

- Two of the pioneers of precise Doppler work were Gordon Walker and Bruce Campbell, at the University of British Columbia. They had a clever idea for wavelength calibration: Before the starlight goes into

the camera, make it go through a container of gas, which has its own spectral absorption lines.

- The camera image shows both the star's absorption lines and the gas's right on top of each other. That way, if the camera shifts around, or expands or contracts, it'll shift both the star's and the gas's lines in precisely the same way.

- You can focus your attention only on any shifts in the star's spectrum relative to the gas spectrum. If you see the star shift, but not the gas, you can be pretty sure that it's due to the motion of the star and not just the rattling around of your telescope and camera. This trick is called the absorption cell method for precise Doppler measurements.

- By this time, searching for exoplanets was considered a flaky business, because of all the previous false claims. They struggled to get the telescope time and funding to pursue a big project. They were limited to monitoring about 30 stars. They did find some potentially interesting signals but never managed to convince themselves or others that they were definitely from planets. We know now that a few of those candidate signals were, in fact, from exoplanets.

- Other groups had different ideas for wavelength calibration. For example, you can combine the starlight with light from a well-understood light source in your laboratory—a glowing lamp that is engineered to produce bright lines in the spectrum with known wavelengths. Those bright lines allow you to sense tiny shifts in the positions of the star's absorption lines. This is called the emission lamp method for precise Doppler observations.

- In 1988, a team led by David Latham of the Smithsonian Astrophysical Observatory used the emission lamp method to identify the Doppler wobble of a star called HD 114762. This star definitely had some small object orbiting it—smaller than any other object that had ever been found with the Doppler method.

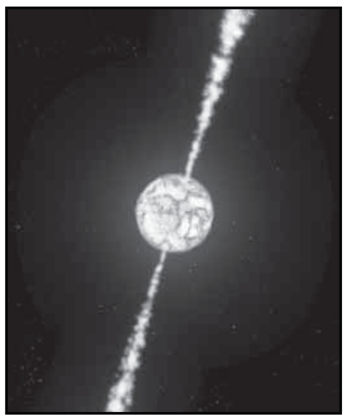
- The object's minimum mass was 11 times the mass of Jupiter, so they knew it could be a giant planet. But they were reluctant to call it a planet; instead, they called it a brown dwarf, which is a star that has such a small mass that its interior doesn't have a high enough pressure or temperature to ignite the nuclear fusion reactions that usually cause stars to shine. But brown dwarfs typically have a mass of 20, 30, or up to 80 times the mass of Jupiter, not 11.

- At the time, Latham's result was not perceived as a planet discovery; it was perceived as a probable brown dwarf discovery. There is no longer much reason to doubt that Latham's team discovered the first exoplanet. But this is only from our retrospective view.

The Discovery of a Neutron Star

- In 1991, astronomers Aleksander Wolszczan and Dale Frail, who were working in a different branch of astronomy, announced the discovery of 2 planets, both about 4 times the mass of the Earth. The evidence was watertight and convincing. But the star was not an ordinary star like the Sun—it was a neutron star, which is a type of dead star.

- Interestingly, the evidence was not based on the astrometric method, or the Doppler method or the transit method; it was based on a method that only works for neutron stars. Some neutron stars emit radio waves, in a series of short pulses of energy, with extremely regular timing. These special neutron stars that emit regular pulses are called pulsars.



Some neutron stars, which are a type of dead star, emit regular pulses and are called pulsars.

- Wolszczan and Frail measured the times of those pulses as they

reached the Earth, and they showed that the pulses were not arriving at a regular rate. Sometimes they arrived early, and sometimes they arrived late, relative to when you would think they should arrive if they were being emitted in a steady stream.

- The neutron star is moving around the center of mass of the planetary system, and when the neutron star is farther away from the Earth, it takes longer for its pulses to reach the Earth. When it's on the near side of its orbit, the pulses don't have as far to travel, so they reach the Earth a little early.

- It's difficult to imagine a less hospitable place for life than the pulsar planets. Up in the sky, there would be no normal star; instead, there would be a tiny black dot spewing out a maelstrom of radio waves, X-rays, and lethal doses of radiation. Nobody knows how these pulsar planets formed.

- For a time, in the early 1990s, scientists wondered whether pulsar planets would become a major field within astronomy—but they never did. No other pulsar planets have ever been discovered, except for a single special case. With so few examples, it's difficult to understand the origin and significance of the pulsar planets and whether they have anything to do with normal planets.

The Birth of Exoplanetary Science

- The year traditionally taken to be the birth of exoplanetary science is 1995. Michel Mayor and Didier Queloz, astronomers from the Geneva Observatory in Switzerland, had been improving the emission lamp technique for Doppler measurements. Earlier, they had helped David Latham observe his star. Now, they decided to go planet hunting themselves, and they had a near monopoly on a telescope in France that allowed them to look at many more stars than Campbell and Walker.

- Because their measurements were only good enough to find giant planets, they thought they were in for a very lengthy project, lasting decades, because giant planets in the solar system all have orbital

periods of a decade or more. But they actually found their first planet after just a few months.

- One of their stars, a sunlike star named 51 Pegasi, was moving from one place to another with an amplitude of 50 meters per second and a period of only 4.2 days. This signal could be explained as coming from a planet with a minimum mass in between that of Saturn and Jupiter, but its orbital distance would be only 1/20 of the distance from the Earth to the Sun.

- Being so close to the star, the planet around 51 Peg would be heated to nearly 2000° Fahrenheit—a temperature that's usually associated with a small star, not a planet. This was our first glimpse at a so-called hot Jupiter.

- The astronomical community was skeptical about this discovery, because of the history of the field as well as the freakish nature of the object. But soon afterward, the Doppler signal was confirmed by a pair of astronomers in the United States, Geoff Marcy and Paul Butler. In addition to improving on Campbell and Walker's method, they also found many planets once they realized that there could be very short-period planets lurking in their data.

- Another American group, led by William Cochran at the University of Texas, started finding planets, too. Within a few years, dozens of giant planets emerged, all of which were massive and had orbits much smaller than any of the giant planets in the solar system. And some of them had very eccentric orbits, unlike the circular orbits seen in the solar system.

- For the next 10 years, the Doppler technique was the most prolific technique for exoplanet discovery. The field began to grow exponentially, in terms of the expansion in the number of planets known, the precision in the techniques, and the number of scientists working in this area. The next technique to mature, around the year 2005, was the transit technique—detecting the miniature eclipses of stars by their planets.

Suggested Reading

Croswell, *Planet Quest*.

Latham, et al, "The Unseen Companion of HD 114762."

Mayor and Queloz, "A Jupiter-Mass Companion to a Solar-Type Star."

Wolszczan and Frail, "A Planetary System around the Millisecond Pulsar PSR1257+12."

Questions to Consider

1. Would it be fair to say that the pulsar planets were the first exoplanets to be discovered, or should the Doppler discoveries be regarded as the beginning of the field?

2. Prior to 1995, most astronomers were skeptical that finding exoplanets would be a rewarding activity. Was this skepticism justified, given what was known at the time?

The Misplaced Giant Planets

Lecture 5

For many centuries, the only planets that were known were the planets of the solar system. Naturally, this set our expectations for planets around other stars. Among those expectations are that planetary orbits should be very nearly circular; they should be aligned with each other; and the small rocky planets should be interior to the giant gaseous planets. That's why the earliest known exoplanets—such as and other misplaced giants—were so surprising. In this lecture, you will learn about the theory of planet formation and how it tries to explain the patterns that we see in the solar system, as well as observations of very young stars.

Hot Jupiters

- The planet 51 Pegasi b is the first known example of a category of planets known as hot Jupiters. Hot Jupiters are called "Jupiters" because they're comparable in size and mass to Jupiter and are likely composed mainly of hydrogen and helium gas, like Jupiter. They're called "hot" because they are so close to their stars that they're getting roasted.

- The planet 51 Pegasi b doesn't have an exterior surface. Like Jupiter or Saturn, the planet is probably gas most of the way down to the center. There is a big difference between the 2 sides of the planet. The half of the planet that faces the star gets roasted until it's red hot—probably about 1800° Fahrenheit. The other side of the planet, facing into the blackness of space, is also pretty hot, because the planet's atmosphere carries some of the heat from the dayside to the nightside, but it's several hundred degrees cooler than the dayside, so it glows less brightly.

- The planet is rotating around its axis every 4.23 days, exactly the same time it takes to complete an orbit. As a result, the planet always presents the same face to the star: The near side enjoys perpetual daytime, and on the far side, it's permanently nighttime.

This matching of the rates of rotation and revolution is called tidal synchronization. This happens whenever you have 2 astronomical bodies that are orbiting each other closely enough and you wait long enough.

- It is because 51 Pegasi b is tidally locked that it rotates once every 4.23 days. This is a lot slower than Jupiter, which spins every 10 hours. For this reason, and also because it's being heated by the star to such an extraordinary degree, astrophysical theorists tell us that it will look very different from Jupiter. They have used mathematical models of fluid flow around a hot, tidally synchronized planet to try to anticipate what the planet would look like.

- According to these models, there will not be lots of thin horizontal bands, like we see on Jupiter. Instead, we'll see just 2 or 3 bands, and possibly huge vortices at the north and south poles. And the winds will be much stronger on 51 Pegasi b than they are on Jupiter, blowing with a speed of several kilometers per second, or thousands of miles per hour, from west to east, circulating the intense heat of the star all the way around the planet.

The planet 51 Pegasi b is the first known example of a category of planets known as hot Jupiters, which are comparable in size, mass, and composition to Jupiter.

The Theory of Planet Formation

- Hot Jupiters, such as 51 Pegasi b, are giant planets where we didn't expect them. One reason we didn't expect them there is because our solar system doesn't have a hot Jupiter. A second reason we didn't expect them is that our expectations were also based on the theory for giant planet formation that had gradually been developed since the 1960s.

- Stars, like the Sun, have not been shining forever. They haven't been around since the big bang. Stars have to be born—they form out of hydrogen and helium gas that's floating around the galaxy. If these gas clouds become too dense, then their own gravity causes them to collapse, shrinking the cloud until it gets smaller and smaller and eventually gets dense enough that the interior is hot enough, and has a high enough pressure, to ignite nuclear reactions. That's when a star is born.

- Starting in the 1980s, it became clear that very young, recently formed stars are always surrounded by spinning disks of gas and dust. At first, the evidence was indirect—an excess infrared glow that couldn't be attributed to the star itself—but later it became possible to make images of these disks and their silhouettes. These disks contain some of the leftover material from the original collapsing gas cloud that has not yet fallen onto the newly born star.

- The collapse of the cloud isn't so straightforward. The material can't just all pull itself together immediately into a tight little ball. The reason is the principle of physics known as the conservation of angular momentum.

- The hydrogen and helium in the gas cloud are not just sitting still; they are moving randomly around, including some slight rotational motion. When the cloud collapses, the conservation of angular momentum says that the shrinking size causes the rotation to be amplified. The material spins faster and faster as it collapses, and by the time its size approaches the size of a star, it's spinning very quickly, and that slows down further collapse.

- Around a star, these circulating flows of gas—these spinning disks—seem to last 5 or 10 million years. These disks go by many names. Some call them accretion disks, to emphasize that the material is accreting onto the star—that is, falling onto and accumulating on the star. Others call them protoplanetary disks, because it's almost certain that these disks are the environments in which planets are born.

- There's plenty of material in these protoplanetary disks to make the planets. In addition to the hydrogen and helium gas, which is by far the main component, there's a sprinkling of heavier elements (such as carbon, oxygen, nitrogen, silicon, and iron) that exist as specks of dust or ice, made of rocky minerals, water, methane, and ammonia. There is enough of those heavier elements to make all the planets we see in the solar system and have plenty left over.

- But how? Does the material in the disk just collapse, like the star did? According to the leading theory of planet formation, the answer is no. Planet formation is thought to work very differently from star formation.

- Planets are thought to form not by the collapse of a large part of the protoplanetary disk but, rather, by a more bottom-up process. They start out as single grains of dust. Over time, these dust grains settle down into the midplane of the disk. Soon, the dust grains form a thin layer at the midplane of the disk, and that layer has a high enough density that that dust grains occasionally collide with each other.

- Now and then when they collide, they stick, becoming bigger and bigger. Eventually, you get a particle the size of a grain of sand, then a pebble, a rock, a boulder, and over millions of years, the grains of dust have grown to the size of a planet like the Earth.

The Planetesimal Hypothesis

- The idea that planets form through the growth of smaller bodies, through colliding and sticking, is called the planetesimal

hypothesis. This theory explains 2 of the 3 patterns in the solar system: Planetary orbits should be very nearly circular; planetary orbits should be aligned with each other; and the small rocky planets should be interior to the giant gaseous planets.

- Because the spinning protoplanetary disk is flat, the planets that eventually form will naturally have orbits that lie within the plane of the disk. This explains why the orbits are so closely aligned. It also explains why the orbits are circular. That's because all of the material in the disk goes around in circular orbits, so naturally, the planets that form out of that material will also have a circular orbit.

- The solar system planets have circular orbits because they formed in a disk in which all the material was flowing on circular orbits, and even if a planet started out on an elliptical orbit for some reason, the friction-like interaction between the disk and the growing planets would've gradually caused the planet's orbit to become a perfect circle.

Core Accretion

- What about the third pattern in the solar system—the fact that the 4 small rocky planets are much closer to the Sun than the 4 gaseous giant planets? The part of the theory that tries to explain this is called core accretion.

- Imagine a growing planet. Planetesimals are colliding and coming together and accreting more and more material. If the growing planet manages to surpass the Earth in size, if it gets to be more than about 10 times the Earth's mass, then it starts growing much faster. That's because 10 Earths is about the size where the planet's gravity is strong enough to begin accreting the surrounding hydrogen and helium gas, and the gas is much more abundant than the dust.

- The planets that grow bigger than 10 Earths very quickly swell up and become gas giants, hundreds of times more massive than Earth. The crucial thing for this theory is that it's only possible to reach that threshold mass if you're far away from the star, where

it's cold enough to be below the freezing temperatures of water, ammonia, and methane. That gives you a lot more solid material to work with. If you're too close to the star, those materials exist only as gases, not solids.

- In other words, the solar system has a snow line, kind of like a mountain. Beyond the snow line, there's a lot of "snow" to pack onto a growing planet and make it big enough to start accreting gas, but inside the snow line, you don't have enough solid material.

- In this theory, the reason why the outer planets are bigger is that they formed beyond the snow line, where there was enough material to make a bigger solid core—big enough to accrete tons of gas. In our solar system, the snow line is somewhere between the orbits of Mars and Jupiter, forming a boundary between the rocky planets inside and the gas giants outside.

- This is why it was such a shock to find a gas giant planet like 51 Pegasi b sitting so close to its parent star: The last place you'd expect to find a giant planet is way inside of the snow line, with heat more like Death Valley than a snow-covered summit.

- In addition to the hot Jupiters, there's another type of misplaced giant. Soon after the discovery of 51 Pegasi b, astronomers began finding giant planets on very elliptical orbits, not even close to circular. This, too, violated one of the expectations of the theory of planet formation.

- The best example is a planet known as HD 80606b, which was discovered in 2001 by a team led by Swiss astronomers. This is a gas giant planet about the same size as Jupiter and about 4 times as massive, so it's a relatively densely packed planet. It orbits a star very similar to the Sun, with a period of about 111 days.

- This is already peculiar. Jupiter's orbit is 12 years, so HD 80606b is too close to its star for comfort. It's inside the snow line. But even weirder is that the orbit is highly elliptical. The eccentricity—which

ranges from 0 for a circle to 1 for an orbit so skinny that it looks like a straight line—of HD 80606b is an amazing 0.93.

- This planet makes a mockery of the theory of planet formation in 2 ways: by being a gas giant interior to the snow line and by having such an elongated shape for its orbit. It's a great demonstration of Kepler's first and second laws but a terrible blow to the theory of planet formation.

Suggested Reading

Armitage, *Astrophysics of Planet Formation.*

de Pater and Lissauer, *Planetary Sciences*, section 2.6.

Mayor and Queloz, "A Jupiter-Mass Companion to a Solar-Type Star."

Mazeh, "Observational Evidence for Tidal Interaction in Close Binary Systems."

Ryden and Peterson, *Foundations of Astrophysics*, section 4.2.

Questions to Consider

1. How might everyday life be different if the Earth's rotation were tidally synchronized with the Moon's orbit? What if Earth's rotation were synchronized with its own orbit around the Sun?

2. If the solar system had a hot Jupiter, would ancient astronomers have been able to detect it? What would be the best way to search for such a planet?

3. Do you think the core accretion theory provides natural explanations for the patterns in the solar system, or is it instead a case of contriving a story to explain the facts?

Explaining the Misplaced Giant Planets

Lecture 6

The misplaced giants are giant planets, many of them as large as Jupiter or even larger, whose orbits are surprisingly close to their parent stars—closer than you might have guessed, based on observations of the solar system, and closer than was expected, based on the prevailing theory of planet formation. Many of them have highly eccentric orbits, instead of nearly circular orbits. We now know of hundreds of these misplaced giants. As you will learn in this lecture, trying to explain how these planets got into these peculiar orbits is a major preoccupation of workers in this field.

Problems with the Theory of Planet Formation

- The theory of planet formation has 2 main parts: The first is planetesimal formation, in which tiny grains of dust within the protoplanetary disk stick together and grow into larger and larger objects, until they are planet-sized rocky masses. Then, if one of those objects manages to grow larger than about 10 times the mass of the Earth, then it sucks up all of the hydrogen and helium gas in the vicinity and becomes a gas giant planet. This second part is called core accretion.

- According to the theory, core accretion is only supposed to happen beyond the snow line, because that's the only place where it seems plausible for a planet to be able to grow to that critical size of about 10 Earth masses.

- This theory had some problems even before the discovery of the misplaced giants. In particular, how do dust particles stick together and grow until they are the size of planets? You might have found it a little difficult to swallow that this growth in size—by a factor of something like a trillion—just happens spontaneously.

- Chemists and physicists who study dust coagulation have found that there's no problem getting the dust to stick together into sand grains,

and then into pebbles, and rocks. But once the rocks reach the size of about a meter, there are a few problems. First, when big rocks collide, they don't stick together. Second, meter-sized bodies should fall onto the star, because they're too big to be carried along by the gas.

- These 2 problems together go by one name: the meter barrier. It's the biggest unsolved problem in this theory, and it was known even before the discovery of exoplanets.

- There are many ideas for how to overcome this problem, but we don't know if they're correct. Currently, it is suspected that the solution is that our mental picture of the conditions in the disk is wrong; what it's really like is not a steady wind of hydrogen and helium pushing all these particles around in their orbits but, rather, a big turbulent storm, whirlwinds and hurricanes of hydrogen and helium throughout the disk, and these vortices can concentrate the dust particles into very dense conglomerates.

- In the growth process, the dust sticks together into rocks, and then the rocks have to somehow get concentrated into calm regions where they can pile up into kilometer-sized objects, and then those objects are massive enough for gravity to take over and pull them together into planets.

- To make a gas giant planet, all of this has to happen while the gaseous protoplanetary disk is still there—before it all spirals onto the young star or gets blown out into space by the intense radiation of that young star or the radiation from neighboring stars.

- When we look at young stars with our telescopes and search for evidence of these disks, we only find them when the stars are younger than 5 or 10 million years. So, all of those various steps in the process of planetesimal formation take place while a clock is ticking.

- If they can't form large bodies within a few million years, then a planet will never be able to swell up and become a gas giant, because there's no more gas to be found. A few million years might

sound like a long time, but it's actually a brief interval, from the star's point of view.

Gravitational Instability

- Because of these problems—the meter barrier and the ticking clock—a small group of scientists has proposed an alternative theory of giant planet formation. It's called gravitational instability, and its leading proponent is Alan Boss, who works at the Carnegie Institution of Washington.

- In his theory, in order to form a giant planet, you don't have to wait for the dust to grow through all these shenanigans into larger and larger rocky bodies. Instead, giant planets form directly from clumps of gas in the protoplanetary disk. He imagines that the gas in the protoplanetary disk is dense, and due to its own gravity, it becomes unstable: One region happens to be denser than the surrounding regions, so its gravity causes that region to contract, making it even denser, which increases the gravitational force still further, until you have a tight, small ball of gas—a newly born giant planet, without needing any rocky core to seed this process.

- The problem is that the theory seems to require highly contrived conditions within the disk—just the right density, just the right temperature. This theory seems to have even more severe problems than the core accretion theory, which is why it has not gained many adherents.

- Instead, the consensus among theoreticians is that the combination of planetesimal growth and core accretion, despite all the issues they have, is still the best explanation available for the formation of planets.

Planet Scattering

- The theory of planet formation says that giant planets should only form beyond the snow line—so isn't this another big problem for the theory? Wouldn't you think that the discovery of so many giant

planets so far away from where they're supposed to be would be enough to cause us to tear up the theory?

- The current consensus is that the planet formation story is actually fine; it's just that we were missing a few chapters at the end. Nobody had paid enough attention to what might happen to planets after they form. As it turns out, there are many important processes that can rearrange planets and change their orbits, even billions of years after they form.

- In fact, within just a few months of the discovery of 51 Pegasi b, theorists came up with 2 different ways to explain the close-in planets. The first scenario requires several giant planets to exist around the star. We need to imagine that there's enough material to form 2 giants, or even 3 or 4.

- You start out with these giants just where they are supposed to be: beyond the snow line, on nearly circular orbits. And for a long time, the planets all revolve around the star in what seems like a harmonious arrangement—but they happen to be orbiting just a little too close to each other, and over billions of years, the configuration proves to be unstable.

- In addition to the star's gravitational force on each planet, the planets exert gravitational forces on each other, altering their orbits. All the neat and tidy properties of the initial system could be lost: The orbits could become tilted and elongated. Maybe that explains the elliptical orbits that we see.

- In fact, this might also explain the close-in planets, including the most extreme cases, the hot Jupiters. Occasionally, the gravitational interactions between planets can lead to really close encounters, near-collisions, during which the gravitational forces are very strong and can slingshot the planets around. Maybe a giant planet gets scattered onto an eccentric orbit, one end of which is so close to the star that tides become important, heating up the planet at the expense of its orbital energy, causing the orbit to shrink.

- Theorists have come up with many variations on this theme. For example, you don't really need a close encounter between 2 planets; the gravitational interactions between planets can accumulate gradually, over millions of years. Or, a companion star can provide the perturbation, rather than a second planet.

- These variations can be lumped together under the name "planet scattering." You have a few large bodies—whether they are several planets, or a planet and a nearby star—and they throw each other around due to their own gravity.

- This story for the origin of the misplaced giants and their elliptical orbits has the virtue of simplicity. But that doesn't mean it's correct. Many astronomers find planet scattering to be too contrived. Arranging for just the right interactions to fling a giant planet onto an appropriate orbit—close enough for tides to be important, but not so close that the planet is destroyed—seems unlikely.

- An even more serious issue is that there are many giant planets whose orbits are small enough to be inside the snow line, yet too far from the star for tides to be important. Planet scattering has a hard time explaining those cases. So, even if it happens sometimes, it probably doesn't explain the full range of possibilities.

Planet Migration

- In that same frenetic period just following the discovery of 51 Pegasi b, a second and completely different idea was proposed for shrinking the orbit of a giant planet. This idea relies on the gaseous disk from which the giant planets form.

- The relationship between a growing planet and the gaseous protoplanetary disk is complicated. In the beginning, when the solid material is in the form of microscopic dust grains, the dust simply blows in the wind, getting carried along by the gas. Later, when the solids have grown into the size of large rocks, they're too big to flow along with the gas, so they go at a different and more

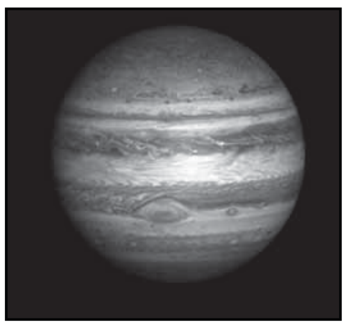
random speed and feel the force of aerodynamic drag—and this is potentially fatal for the rocks.

- Even later, after the rocks somehow overcome the meter barrier and grow into planet-sized objects, there's a new phase in this relationship with the disk. The planet's gravity is strong enough to pull on the nearby gas and change the way the gas is distributed in the disk. It sculpts patterns in the disk.

- The planet starts rearranging the mass of all the gas in the disk, and crucially, this also changes the gravitational force with which the disk pulls back on the planet. The planet and the disk can start exchanging energy and momentum. The planet has become a real player in the game of gravitational push and pull.

- The outcome is that the planet can, in the right conditions, transfer its orbital energy and momentum to the disk—and thereby shrink its orbit, spiraling inward to become a misplaced giant. This theory is called planet migration. We say that the planet "migrates" from its initial location, beyond the snow line, to a much smaller orbit, by surrendering its energy to the disk.

- The basic idea of planet migration can be traced back to a paper by Peter Goldreich and Scott Tremaine that was published in 1980, well before the dawn of exoplanetary science. This paper basically languished in the literature until the misplaced giants were discovered. Since then, it's been a must-read for any theorist in exoplanetary science. In 1996, Doug Lin, Peter Bodenheimer, and Derek Richardson used this theory to try to explain 51 Pegasi b.



Nobody knows for sure what prevented our own Jupiter from becoming a hot Jupiter.

- Over the years, as calculations of the gravitational interactions between planets and protoplanetary disks have been performed with increasing accuracy, migration seems ever more powerful as a way to shrink orbits—and even inevitable. Indeed, the problem has become how to stop it. Why does a giant planet not spiral all the way onto the star and become engulfed? What prevented our own Jupiter from becoming a hot Jupiter?

- Nobody knows for sure. Maybe the outcome depends sensitively on exactly how massive the disk is, or its temperature, or some other detail that varies from star to star, and the Sun just happened to have a relatively inactive disk.

- As for why hot Jupiters didn't just spiral all the way in and plop into the star, maybe the inner part of the protoplanetary disk gets ruptured by a young star's intense radiation, or strong magnetic field, and when a giant planet spirals in far enough to reach that evacuated part of the disk, there's no more gas to interact with, and it stops.

Suggested Reading

Armitage, *Astrophysics of Planet Formation.*

de Pater and Lissauer, *Planetary Sciences*, chap. 13.

Lin, "The Genesis of Planets."

Perryman, *The Exoplanet Handbook*, chap. 7.

Questions to Consider

1. Try to list all the basic steps in the core accretion theory for the formation of gas giant planets. Which step is the most poorly understood?

2. Which seems more plausible to you as an explanation for the misplaced giants: close encounters between planets or interaction with the protoplanetary disk? Can you think of any ways to test whether either of these theories is correct?

The Transits of Exoplanets

Lecture 7

One of astronomers' favorite techniques for studying exoplanets is observing eclipses: those rare and precious events when a planet's orbit carries it right in front of the disk of its parent star, and the planet blocks a small fraction of the starlight that would ordinarily reach us. The march of a planet across the disk of its parent star is called a "transit," the term for a partial eclipse of a big object by a much smaller object. After the first discoveries of exoplanets, there was a period of intense anticipation as many astronomers sought to be the first to detect the transit of an exoplanet—the subject of this lecture.

Detecting Transits

- The basic characteristics of the transit signal are as follows. The fraction by which the star gets dimmer is the area of the planetary disk divided by the area of the stellar disk—so it's the ratio of their radii, squared. The duration of the event depends on the size of the star, the planet's orbital speed, and the exact track the planet takes across the star.

- The main drawback of the transit method is that it takes a special coincidence for the planet's orbit to be oriented just right for us to see transits. The probability is equal to the size of the star divided by the size of the orbit, which is only 0.5% for the Earth's orbit around the Sun but is as high as 10% for a hot Jupiter.

- Once the first few hot Jupiters were discovered, with the Doppler method, everyone knew that it wouldn't be long before at least one of them would show transits. By 1999, about 10 hot Jupiters had been discovered, and one of them turned out to be transiting. The name of that fateful planet is HD 209458b.

- The detection of the transit of HD 209458b was extremely important for several reasons. First, it confirmed beyond any doubt

that the star's Doppler signal was really due to a planet. In the late 1990s, some astronomers worried that we were being fooled by the Doppler signals—that the apparent back-and-forth motion was really some other phenomenon. Detecting the transits of HD 209458b with exactly the right period, duration, and change in brightness proved that it really is a planet—and, by extension, that the other Doppler planets were probably genuine, too.

- Second, we could finally measure the size and the mass of an exoplanet without any ambiguity. Based on how much light it blocks, we know that the size of HD 209458b is 40% larger than Jupiter. The mass is about 30% smaller than that of Jupiter, based on the combination of the transit and Doppler data.

- Once we know both the size and the mass of the planet, we can calculate the mean density of the planet: the mass divided by the volume of the planet. And that gives us a clue about what the planet is made of.

- The 2 big gas giants—Jupiter and Saturn—have mean densities of about 1 gram per cubic centimeter. Neptune and Uranus have mean densities of 1.5 grams per cubic centimeter. The rocky planets, like Earth, have mean densities around 5 or 6 grams per cubic centimeter. By measuring the mean density of an exoplanet, we can categorize it as a planet likely to be gaseous, or rocky, or somewhere in between.

The Theory of Hydrostatic Balance

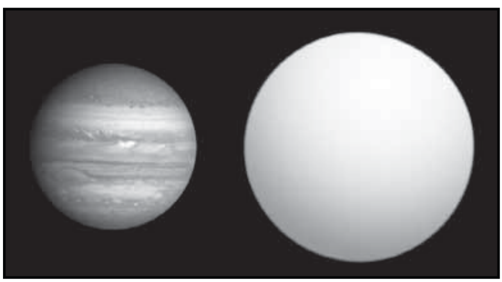
- The mass of HD 209458b is 30% smaller than that of Jupiter, and the size is 40% larger. It has less mass, and it's packaged into a larger volume, so its mean density is low—only 0.5 grams per cubic centimeter. That's less than Jupiter's or Saturn's density, and less than anybody expected it would be. This was the first known example of what turns out to be a pattern: Many of the hot Jupiters are bloated. They're big, puffy planets, for unknown reasons.

- It's fairly straightforward to calculate how big a planet should be, once you know what it's made of. You make a mathematical model that's based on the principle of hydrostatic balance: At every position inside the planet, material is being pulled inward by the planet's own gravity, but it is not actually falling down toward the center of the planet because the pressure of the material is strong enough to resist the gravitational pull. Hydrostatic balance is the balance between gravity, which pulls down and tends to compress the planet, and pressure, which develops whenever you try to compress a substance.

- Those simple models predict that HD 209458b should be slightly smaller than Jupiter, not 40% bigger. These models also fail to predict the correct sizes for dozens of other planets, so something important must be missing from those models.

- The main clue about what's missing is that among these puffy planets, the puffiest are also the ones that are closest to their stars. This suggests that there's something about the proximity to the star that is causing the planets to puff up.

- You might be thinking that it's the heat from the star. The planet is being baked on one side, and that heat is causing the material to expand. It sounds good, but it turns out to be not so simple. The problem is that in order to puff up the planet, you need that heat to reach way down into the interior of the planet. If you only heat the surface, the outer atmosphere gets hot and then immediately radiates that heat into space. It doesn't cause the whole planet to puff up. The atmosphere is too thick, and the heat doesn't penetrate.



The planet HD 209458b is 40% bigger than Jupiter, and its mass is 30% smaller than Jupiter.

- Theorists have tried to dream up ways to transport the star's heat into the depths of the planet. Maybe the planet has giant storms, but instead of being confined to the outer layers, the winds blow down into the planet, tens of thousands of miles. That would ferry hot material from the surface into the depths, where it could cause the whole planet to expand. But there are no realistic climate models for these planets that actually have these strong vertical winds.

- Another idea that has been proposed is that it's not really the direct heat from the starlight that's important but, rather, an electrical heating effect. If you run electrical current through a material, then the material will resist the current, to some degree, and that resistance causes the material to heat up.

- We don't have enough data to decide which of these theories is correct—or if both of them might be wrong. Nobody is even sure what type of data might settle the question. We have no way in the foreseeable future to directly observe the weather on these planets or to detect any electrical activity in their atmospheres, so we are currently stuck.

- Not all of the giant planets we've detected are bloated. The giant planets that are farther away from their stars seem to have mainly normal densities, of around 1 or 2 grams per cubic centimeter. And we've found very massive planets that have much higher densities. But we expected the densities of massive planets to be very high.

- The amazing consequence of the theory of hydrostatic balance is that a planet the size of Jupiter can have any mass, from Jupiter's mass to 100 times Jupiter's mass. Over that range, gravity is able to compress all that material into a roughly Jupiter-sized ball.

Transit Photometry

- The planet HD 209458b, and many other planets, were originally discovered with the Doppler technique. Then, after discovering the planet, the star was monitored to see if the planet happened to transit. That's a good way to find transiting planets, but it does have the

drawback that you have to monitor many stars before you'll be lucky enough to find a transiting planet, because the probability is so low.

- If you are exclusively interested in transiting planets because you want to measure masses and sizes of planets, then it makes sense to search for transits first, instead of looking for the Doppler signal first. This makes even more sense when you realize that the equipment required to detect a transit is much simpler—and less expensive—than the equipment required to detect the Doppler signal.

- It dawned on many astronomers that it makes sense to invert the order of discovery: Use humble telescopes to identify transits and measure planet sizes, and then deploy the precious time on the world's biggest telescopes to measure the planet masses.

- Think about the requirements for such a survey for hot Jupiters, for example. About 1 out of every 200 sunlike stars has a hot Jupiter, and about 1 out of every 10 of those hot Jupiters will have its orbit oriented the right way to transit. So, you need to search at least 2000 stars to have a decent chance of finding 1 transiting hot Jupiter. And you need to monitor those 2000 stars as continuously as possible for a few weeks (a few times the orbital periods of the planets). And you need a precision good enough to detect a dip in brightness of around 1%.

- Starting in the mid-1990s, astronomers began building small, automated telescopes, in some cases no bigger than department store telescopes or even telephoto lenses for ordinary cameras. They scanned the sky, keeping tens of thousands of stars under surveillance as constantly as they could, although they had to put up with interruptions due to bad weather or the Sun rising above the horizon for half the day.

- By the early 2000s, these transit surveys started striking gold. As of now, they've found nearly 200 planets—mostly hot Jupiters, but also some smaller planets. The 2 most productive surveys are the

Wide Angle Search for Planets (WASP) and the Hungarian-made Automated Telescope (HAT).

- Then, the transit surveyors got fed up with bad weather, and with the relentless cycle of day and night, and with the corrupting effects of the Earth's atmosphere on our measurements. So, they went into space. In 2006, the European Space Agency launched a satellite called CoRoT, and in 2009, NASA launched one called Kepler, both of which were designed to search for transiting planets.

- Between about 2010 and 2014, transit photometry was the most prolific means of planet detection. We now know of thousands of transiting planets—and we've measured masses for a few hundred.

Suggested Reading

Hogg, "Le Gentil and the Transits of Venus, 1761 and 1769."

Howard, "Observed Properties of Extrasolar Planets."

Seager, ed., *Exoplanets*, chap. 4.

Questions to Consider

1. Pretend that you are viewing the solar system from 10 light-years away in a random direction. How likely would it be that you could observe transits of Venus? How often would they occur, and how long would each transit last? How much fainter would the Sun get during the transits?

2. Knowing only the size and mass of a planet, is it possible to draw any firm conclusions about what the planet is made of? Could our inferences about which planets are gas giants and which are rocky be mistaken?

Sniffing Planetary Atmospheres

Lecture 8

Although we're always pleased to discover exoplanets, we are especially fond of transiting exoplanets, because transits offer more information than the other techniques. With the transit method, we can determine the planet's mass and size. But how do we figure out what's in the atmospheres of these faraway planets? What are these planets made of? These are important questions for understanding the planets and the conditions under which they formed, and, as you will learn in this lecture, they might also be important in the search for life on other planets.

Spectroscopy

- In astronomy, how do we figure out what something is made of? With a few rare exceptions—including when the Apollo astronauts brought back some rocks from the Moon—we can't bring the objects we see through our telescopes into a laboratory for testing.

- The answer is spectroscopy. We figure out what things are made of by studying the spectrum of the light they emit or absorb. The light brings the information to us; we don't need to send rockets to fetch the material itself.

- We start with the fact that everything is made of atoms. Atoms come in many different types, ranging in mass from the lightest ones—hydrogen, helium, lithium, beryllium, boron, carbon, nitrogen, oxygen—to the heaviest naturally occurring atom, uranium. Atoms have 2 parts: a nucleus, made of protons and neutrons, and electrons, much lighter particles that whizz around the nucleus at high speed, with their exact location being blurred out into an electron cloud.

- The nucleus is tiny compared to the electron cloud, but the nucleus is where all the mass is. It's like an incredibly small-scale model of the solar system, with the nucleus as the Sun and the electrons as

planets. But there are some crucial differences between atoms and the solar system, besides the obvious difference in scale.

1. The solar system has only 1 star, but atoms often gang up together to make molecules. The nuclei come close to one another, and they share electrons. So, the electrons make a cloud that envelops all the nuclei in the molecule.

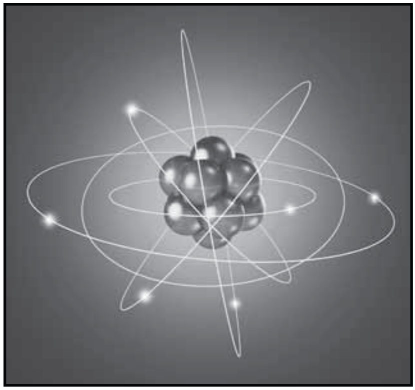
2. The planets in the solar system don't abruptly change their orbits, but electrons do. Electrons can absorb energy from light. Light itself is made of particles called photons. If a photon passes near an electron in an atom or a molecule, there's some chance that the electron will swallow the photon and absorb its energy.

- That gain in energy will cause the electron cloud to spread out, or the electron might gain enough energy to escape the atom altogether, resulting in a free electron sailing through space and an ion, an atom that has lost at least 1 electron. And the reverse can happen, too. An energetic electron can spit out a photon, which carries away some of that energy and leaves the electron in a calmer, shrunken orbit.

- Electrons cannot absorb any photon that might be passing by, and they cannot emit photons with any value of energy they might want. They can only change energy in certain fixed, discrete steps. That's because there are only certain allowed shapes and sizes for the electron cloud around an atom; the electron can't just orbit in any random way.

- This is one of the consequences of quantum theory, the basic laws that fundamental particles obey. Quantum theory is also why the electron's location is blurred out into a cloud in the first place. Both of these strange phenomena arise because electrons around atoms have some properties that are more like waves than like particles—waves that are trapped in the space around the atom. And whenever you trap a wave, there are only certain patterns that the wave can possibly have.

- An electron can only exist with certain fixed values of energy. Those energies depend on the type of atom or molecule. If an electron is



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An atom is composed of a nucleus, which is made of protons and neutrons, and electrons, which are in orbit around the nucleus.

going to absorb a photon, the photon has to have just the right energy to take the electron from one of the allowed levels to another. Likewise, when an electron loses some energy and falls from one level to a lower level, the photon it emits will not have just any energy; its energy will be the difference in energy between the 2 energy levels of the electron.

- The energy levels of an individual nucleus are too high and widely spaced for ordinary light to cause it to change, but in a molecule, where you have more than one nucleus, they can vibrate. These motions, too, are quantized; they can only possess certain fixed values of energy. So, molecules can absorb or emit photons that allow the nuclei to switch between different states of vibration and rotation, too.

- For photons, energy is directly related to color, or wavelength. Blue light has high-energy photons compared to red light. Green photons are in the middle. Each atom or molecule has its own specific, favorite colors of light that it absorbs and emits.

- Atomic hydrogen, for example, prefers a shade of red with a wavelength of 0.6563 microns (millionths of a meter) and also a bluish-green hue at 0.4861 microns and purple at 0.4341 microns. Those colors correspond to the differences between the energies of the allowed states for the electron in the hydrogen atom.

- So, if we see a material that is emitting or absorbing precisely those colors, we can conclude that it's made at least partially of hydrogen.

If you learn the full quantum theory, you can use the spectrum of light not only to figure out how much hydrogen, but also the temperature and pressure of the hydrogen gas.

- That's how we learned the composition of the Sun and other stars and the planets in our solar system, and it's also how we can learn about the atmospheres of exoplanets.

Transit and Occultation Spectroscopy

- For exoplanets, there is a serious practical problem: How are we going to observe the spectrum of the planet? Even with our best telescopes, it's almost impossible to separate the light from a star and its planets in an image—they're always blended together. And the star is much brighter than the planet. With that kind of glare, how can we possibly detect the colors that the planet's atmosphere might be absorbing or emitting?

- The answer is that we rely on transits. With transiting planets, there are 2 ways we can get this information.
    1. We can monitor the spectrum of the star before, during, and after a transit. During the transit, some of the starlight is blocked by the planet and never reaches the Earth, but a small portion of the starlight gets filtered through the planet's outer atmosphere before beginning the long journey to Earth. The atoms and molecules in the planet's atmosphere remove starlight at their favorite wavelengths, slightly changing the observed spectrum from the star. Then, after the transit is over, we see the ordinary, unaltered spectrum of the star. If we do this carefully enough, we can take the difference between the normal spectrum and the transit spectrum and isolate the tiny changes caused by the planet. This technique is called transit spectroscopy. It can potentially tell us which wavelengths the planet's atmosphere is absorbing and, therefore, which atoms and molecules are in the atmosphere.

    2. We can wait about half an orbital period, when the planet has moved over to the far side of its orbit. When it's over there,

we are viewing the planet's dayside, the bright side that's being illuminated and heated by its parent star. Then, there's a good chance that the planet will move directly behind the star. When the star hides the planet from view, we call it an occultation. It's the counterpoint to a transit. If we're pointing our telescope at this system while an occultation is going on, we won't be able to see the planet get hidden, but we can track the spectrum we're receiving and might see that the spectrum changes slightly during the occultation, because the planet's light is suddenly missing. If we take the difference between the spectrum just before or after an occultation and the spectrum during the occultation, we get a glimpse of the light that's being emitted or reflected by the planet.

- These 2 methods—transit and occultation spectroscopy—rely on the trick of using time to separate the starlight from the planet's light, instead of trying to separate the starlight spatially in an image. The planet moves on a predictable orbit, so we know when it is filtering the starlight and when it's being hidden behind the star.

- The variations in starlight during a transit or occultation are typically 1 part in 10,000 or smaller. You need a big telescope, and a careful hand, to make such measurements. But, amazingly, it has been done.

- These methods work best for hot Jupiters, because the planets are so big and their transits and occultations are so frequent. The observations of hot Jupiters have confirmed that their atmospheres are mostly hydrogen and helium, as expected. About half a dozen other atoms and molecules have been detected, including water vapor, ammonia, and carbon monoxide. The data confirm that the temperatures of these planets are more than 1000°, as expected, given how close they are to the star.

- There are some serious limitations of these techniques, at least as they're practiced today.
    1. This method can get spoiled by clouds in the exoplanet's atmosphere. Unfortunately, if a transiting planet has clouds,

then its transit spectrum won't show any specific wavelengths getting absorbed more than others. It'll just show an overall absorption due to blockage by the clouds, but without revealing in any way what the clouds are made of.

2. The signals are really tiny, and often astronomers are using instruments that were not designed for such precise measurements. The field is rife with controversy about whether a given dataset is reliable. But this field is still in its infancy. It's going to take time to improve our instruments and observing techniques before these controversies settle down.

- In the meantime, the controversies have inspired some really creative ways to try to validate these methods by performing transmission spectroscopy on planets for which we already know the contents of the atmosphere. We hope that continued experiments will help us try out different techniques for extracting and analyzing the transit spectra of planets.

- The big question is whether these techniques will ever be powerful enough and reliable enough to go beyond the study of hot Jupiter atmospheres and allow us to study smaller rocky planets similar to the Earth. This would be extremely exciting because it might be our best bet for finding evidence for life on those planets.

- Even if we can't see the surface of an exoplanet directly to search for plants or other signs of life, maybe we can check for indirect signs of life in the atmosphere. The simplest approach would be to look for oxygen. Nobody has thought of any very plausible ways for the atmosphere of a rocky planet to accumulate a lot of oxygen besides having some process like photosynthesis. But maybe there are other possibilities—other molecules, or combinations of molecules, that would allow us to diagnose an atmosphere as being affected by life.

Suggested Reading

Lemonick, “The Dawn of Distant Skies.”

Seager and Deming, “Exoplanet Atmospheres.”

Seager, ed., *Exoplanets*, chap. 18.

Winn, “Strange New Worlds.”

Questions to Consider

1. Which is the more interesting type of information we could gain about an exoplanet: its mass and size or the contents of its atmosphere?

2. It was once thought that learning about exoplanet atmospheres would be impossible. Which properties of exoplanets that are currently thought to be impossible to study will turn out to be amenable to future observations?

Stellar Rotation and Planetary Revolution

Lecture 9

By carefully observing transits (when planets eclipse their parent stars) of exoplanets as well as occultations (when the star eclipses the planet), we can learn an amazing amount of information about planets circling such distant stars. By combining the transit and the Doppler methods, we can deduce the existence of planets, measure their masses and sizes, and even sniff their atmospheres and take their temperatures. In this lecture, you will learn about another aspect of planetary systems that you might not have thought would be possible to measure: stellar obliquity.

Stellar Obliquity

- Obliquity is the angle between 2 planes: the plane defined by the star's equator—that is, imagine extending the star's equator out into space, making a giant flat surface—and the plane that's defined by the planet's orbit.

- The angle between these 2 planes is also called the spin-orbit angle. If the star is rotating in exactly the same way the planet is revolving, then the star's obliquity is 0. If the obliquity is 30°, then the star is tipped by 30°, relative to the orbit.

- Any object that is both spinning and orbiting has an obliquity. The Earth, for example, has an obliquity of 23.5°. Because of its obliquity, the Earth spends part of its orbit with its north pole tipped toward the Sun—summertime for northerners and wintertime for southerners—and 6 months later, the north pole is tipped away from the Sun, and the seasons are reversed.

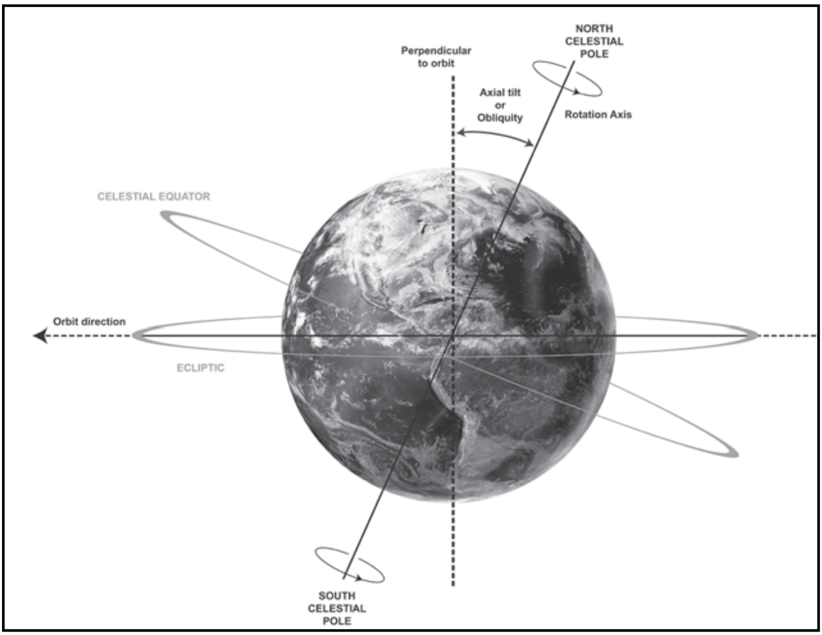
- The Sun has an obliquity, too. The story of how the Sun's obliquity was first measured dates back to the early 17th century, when Galileo began using a then-new technology for astronomy: a telescope. One of his contemporaries was Christoph Scheiner, a Jesuit priest who was another early adopter of this new technology.

- Galileo and Scheiner were probably the first astronomers to use telescopes to observe the Sun. To their amazement, they saw more than just the bright circular disk that they were expecting. They saw black dots on the face of the Sun. And they began arguing vehemently about those black dots.

- Scheiner thought they were planets. He thought the dots were the shadows of a family of small planets, transiting the Sun. Galileo argued that they couldn't be planets. They had to be dark patches in the Sun's atmosphere. Scheiner accepted Galileo's reasoning that the dots were sunspots—relatively dark blemishes on the surface of the Sun.

- Today, we understand sunspots to be magnetic storms: eruptions of the Sun's internal magnetic field through its surface that inhibit the

Earth Obliquity



transport of heat from the depths of the Sun and consequently cause the surface to be cooler and darker.

- After settling their argument, Scheiner painstakingly tracked the motion of sunspots, day after day, as they rotated across the solar disk. From his data, he could tell that the Sun makes a complete rotation about every 26 days—that's the Sun's rotation period.

- His data were good enough to measure the Sun's obliquity. Based on the trajectories of the sunspots, Scheiner saw that in January, the Sun's north pole is tipped slightly toward Earth, and its south pole is tipped out of sight. By June, we can see the Sun's south pole clearly, but the north pole is hidden. The Sun's obliquity is 7.5°.

- There are 2 ways to think about the number 7.5. One is that it is pretty small. The Sun's equator is nearly aligned with the orbits of all the planets. This became part of the collection of evidence that the Sun and all the planets formed from a single spinning disk of material.

- Another way to think about 7.5° is that it's not 0. If everything in the solar system really inherited the same direction of rotation and revolution from that original disk, then why was the Sun tipped at all? The Sun is pretty big. It's not easy to just knock it over; it takes a hefty force.

- Over the years, astronomers offered several possible explanations for that small but seemingly significant tilt. For example, maybe it's a relic of a close encounter with a passing star. Another possible explanation is that we should never have expected perfect alignment between a star and its disk. There's no reason to think that the material that ends up being the Sun is going to be exactly aligned with the material that ends up being the planets.

- All this theorizing about the solar system would be much better grounded if we had the same kind of information about exoplanets. Do the host stars of exoplanets have low obliquities, like the Sun?

- We might also hope to unravel that longest-standing unsolved problem in exoplanetary science: the mystery of the misplaced giant planets, the ones that are found too close to their parent stars.

- The 2 theories for the misplaced giants—planet migration and planet scattering—make different predictions about the stellar obliquity. In planet migration, the orbit should remain lined up with the disk, so the star should have a very low obliquity. In contrast, in planet scattering, all those pushes and pulls that change the planet's orbit are also likely to tilt the orbit, so we should expect to see a wide range of obliquities.

Measuring Obliquity

- How can we actually measure the obliquity of a distant star? With very few exceptions, our telescopes don't allow us to make images of the surfaces of stars. They appear as points of light, so we can't directly watch them rotate.

- We can use a trick, based on a combination of the transit and Doppler methods. During a transit, the planet passes in front of the star, and although we can't actually see the planet's shadow moving across the stellar disk, we know it's happening because we measure the decrease in the star's brightness.

- Imagine watching the same event with special glasses that allow us to perceive very tiny Doppler shifts. The star will suddenly look different: It'll have a red half and a blue half. That's because the star is rotating. At any moment, half of the star is approaching us, and due to the Doppler shift, it appears slightly blueshifted. The other half of the star is receding from us, so it appears slightly redshifted. So, the star is half blue and half red, with the dividing line being parallel to the star's rotation axis.

- When we observe this star with a telescope—as opposed to our magic glasses—the star appears as a single point of light, with all the light from the entire disk blended together, so the red and blue shifts cancel each other exactly, and there's no net Doppler shift.

- But during a transit, the planet steps in front of the blue half of the star and breaks the symmetry. Now, we're missing a little bit of the blueshifted light, and as a result, the starlight we measure is a little bit redshifted. That is, in addition to whatever Doppler shift is produced by the star's orbital motion, we see an extra redshift. We call this extra redshift the anomalous redshift.

- Then, later in the transit, the planet crosses over the middle of the star and blocks equal parts red and blue light. The symmetry is briefly restored; the anomalous Doppler shift vanishes. Then, the planet steps over to the red side of the star and blocks some of that red light, and we observe an anomalous blueshift in the starlight.

- This is exactly what we need to measure stellar obliquities. This sequence of events is for a star with a low obliquity. In that case, the transit causes an anomalous Doppler shift that starts as a redshift for the first half of the transit and then turns into a blueshift for the second half of the transit.

- But if the star has a nonzero obliquity, then we'll see something different. The star is tilted, and the planet's trajectory cuts across the star's rotation axis at a different angle. We don't have a perfect symmetry between blue and red anymore. For example, the planet could spend less time covering the blue side than it does covering the red side, so the anomalous redshift doesn't last as long as the blueshift.

- In fact, if the obliquity is really large, near 90°, then the planet might spend the whole transit in front of the red part of the star, and we would observe an anomalous blueshift throughout the entire event, with no corresponding redshift.

- By tracking the star's apparent Doppler shift throughout a transit, we can measure the angle between the planet's trajectory across the stellar disk and the direction of rotation of the star.

- This trick was invented long ago by astronomers who were studying the eclipses of stars by other stars, rather than by planets. Many stars have companion stars, and sometimes these orbiting pairs of stars eclipse each other. These so-called eclipsing binaries can be studied in many of the same ways that we are now studying exoplanets.

- Richard Rossiter and Dean McLaughlin made the first definitive detections of the anomalous Doppler shift for an eclipsing pair of stars in 1924, so this effect is known as the Rossiter-McLaughlin effect. When 2 stars are involved, the size of the anomalous Doppler shift is measured in kilometers per second. But with planets, the effect is 100 or 1000 times smaller, measured in meters per second.

- By measuring the obliquities of stars with hot Jupiters, researchers have discovered that some systems are well aligned while others seem completely random—but we don't know why. It could be that some hot Jupiters form through planet migration while others form through planet scattering.

- The clearest way forward is to extend these measurements to other types of planets, beyond hot Jupiters. What about planets at more normal distances, farther away from the star? If we see high obliquities for them, too, we'll suspect that the high obliquities are caused by general processes, rather than being specific to hot Jupiters. But if normal planetary systems always have low obliquities and the high obliquities are restricted to hot Jupiter systems, then we can be confident that hot Jupiter production must involve tilting the planet's orbit.

- The challenge is that the Rossiter-McLaughlin effect is difficult to detect for planets that are more distant, or that are smaller than Jupiter. The opportunities to observe transits become less frequent, and the signals are smaller. So, we've had to dream up other ways of gauging the stellar obliquity.

- Among these various techniques, there are about half a dozen obliquity measurements for more “normal” planetary systems—that is, systems that do not have hot Jupiters. Five of them have low obliquities, and one of them has a large obliquity, about 45°.

Suggested Reading

Albrecht, “The Long History of the Rossiter-McLaughlin Effect and Its Recent Applications.”

Winn and Fabrycky, “The Occurrence and Architecture of Exoplanetary Systems.”

Questions to Consider

1. A dark spot (star spot) on the surface of a distant star will cause the apparent brightness of the star to vary as the star spot rotates in and out of view. What are some ways you might tell the difference between the brightness variation due to a star spot and the dip in brightness due to a transiting planet?

2. Consider the finding that many hot Jupiters have orbits that are misaligned with the rotation of their host stars. Does this rule out planet migration theory as an explanation for hot Jupiters? If not, what other types of evidence are needed for a definitive conclusion?

Super-Earths or Mini-Neptunes?

Lecture 10

Because giant planets are easier to detect than smaller planets, up until about 2008, nearly all the newly discovered planets were giants. Our instruments were blind to any smaller planets, and the questions surrounding smaller planets were left unanswered. How common are Neptune- or Uranus-like planets? Can they exist in short-period orbits, close to their parent stars? What about even smaller planets, similar to Earth and Venus? The more thoroughly we began to understand the giant planets, the greater our hunger became to explore smaller planets. In this lecture, you will learn what happened once we improved our planet-finding techniques to study smaller planets.

Midsized Planets

- The first researchers to reach the domain of smaller planets were the practitioners of the Doppler technique. The Americans pursuing this approach used the iodine absorption cell method, in which you pass the starlight through a container of iodine gas and record the spectrum of the star and the iodine at the same time. The idea is that any changes in the instrument or the atmosphere affect both the iodine and the starlight the same way, so by focusing exclusively on the spectral differences between the iodine and starlight, you become immune to many sources of error.

- Meanwhile, the European astronomers took a different tack. They built a spectrograph called the High Accuracy Radial Velocity Planet Searcher (HARPS) for a telescope at an observatory in northern Chile, one of the best places for astronomers, thanks to the dryness of the desert and the stability of the atmosphere.

- HARPS doesn't use iodine. Instead, it minimizes the errors due to changes in the instrument by preventing the instrument from ever changing. HARPS can measure Doppler shifts to within 1 meter per second—and sometimes even better.

- For about 5 years, the European astronomers used HARPS to monitor the Doppler shifts of nearby stars. In 2008, they announced that HARPS had shown that planets the size of Neptune or smaller are very common. Nearly half of sunlike stars have a planet with a size somewhere in the range from Earth to Neptune, with periods less than a year or so. And even more amazingly, these small planets tend to come in pairs or triplets; they come in compact systems of multiple planets.

- It didn't take long for some skepticism to emerge about the HARPS results, because they were so new and because the team didn't release many details. A few Neptune-sized planets had been discovered earlier, but only after years of painstaking data collection and analysis. It seemed too good to be true that the Swiss had found scores of them in just a few years.

- Nevertheless, it was thrilling to have the prospect of a whole new category of planets to play with—planets with sizes in between those of the Earth and Neptune. What was so tantalizing is that our solar system has no such planets. If you rank all the solar system planets in order of size, there's a big jump between Earth and Neptune. Neptune's diameter is 4 times larger than the Earth's, and its mass is 17 times larger. And the Swiss team was saying that the most common type of planet they found is in between those 2.

- Nobody knows what these medium-sized planets are really like. Are they rocky, like giant Earths, or are they more like shrunken versions of Neptune and Uranus? Soon, new jargon emerged in the literature: Were these new planets "super-Earths" or "mini-Neptunes"?

- If we could answer that question, we would learn whether these very common objects have solid surfaces and might therefore be suitable for life. We might also learn something about how they formed. According to the core accretion theory, really small planets—the size of the Earth or smaller—are too small to have accreted much in the way of hydrogen and helium from the protoplanetary disk. Their gravity is too weak to attract the gas in any significant amount.

- But that argument does not apply to these midsized planets. They are massive enough to accrete gas, if there were enough time and enough gas in the environment. So, their composition can't be deduced by mere theorizing. Whether or not a midsized planet has a thick layer of gas depends on the exact way that it formed. That gives another reason to explore these new planets.

The Atmospheres and Interiors of the Solar System Planets

- All of the planets and the Sun originally formed from the same stuff: a cloud of gas, hundreds of light-years across, that was orbiting around the galaxy until eventually gravity caused it to shrink and become denser, and denser, until the Sun was born, along with the protoplanetary disk that would eventually become the planets.

- Everything started out with the same list of ingredients. We can see what those ingredients were by looking at the spectrum of the Sun. Based on the Sun's pattern of absorption lines, we know that this primordial cloud was mostly hydrogen, with a big helping of helium and just a little sprinkling of heavier elements, such as iron, silicon, oxygen, carbon, and nitrogen.

- The Sun is so hot that all of those materials are in the form of gas, even the iron. It's way too hot for liquids or solids. In fact, it's not a gas—it's a plasma, which is a gas that is so hot that a substantial fraction of the elements are ionized. The electrons have boiled off the atoms, so you have free electrons and ions

The Sun is so hot that elements such as hydrogen and helium are in the form of gases, not liquids or solids.

bouncing around. But the planets are much colder. They don't have giant nuclear furnaces burning inside them.

- As the original gas cloud cooled down, the basic ingredients of planets formed: iron and rock; the more volatile elements, water, methane, and ammonia; and the lightweight gases, hydrogen and helium. Gravity caused the densest materials to sink down to the center of a huge planet-sized ball. So, we expect a generic planet to have an iron core surrounded by a "mantle" of rock, a veneer of volatiles, and an atmosphere of hydrogen and helium.

- All the planets in the solar system are variations on this theme, with Jupiter and Saturn following the theme most closely. On the outside, they're almost entirely hydrogen and helium gas—although it's unfair to simply call it "gas." Really, it starts out as a gas in the outermost layers, but as you go deeper and deeper, the pressure increases and it becomes more like a fluid. Eventually, the pressure is so intense that the hydrogen is ionized, and it's a plasma again. Way down deep, the hydrogen is so compressed by all the overlying material that it is predicted to be more like a metal than a gas. Buried beneath all that exotic hydrogen is thought to be a ball of extremely compressed rock and iron.

- Neptune and Uranus probably have a similar structure, but with less hydrogen and helium. Presumably, that's because they didn't accrete as much hydrogen and helium as the larger planets. They formed way out in the nether regions of the solar system, where there wasn't much gas to begin with and where the orbits are wider and slower, causing the planetary growth process to be glacially slow compared to the conditions closer to the Sun.

- Neptune and Uranus have tons of water, methane, and ammonia, though—about 10 or 20 times as much of the volatiles as the rock and iron at their centers. That's why sometimes Neptune and Uranus are called ice giants instead of gas giants.

- The smaller planets—Mercury through Mars—are so puny that they can't hold on to any hydrogen and helium. Their gravity is too weak, and those gases are too light. So, even if the Earth did start with a lot of hydrogen and helium, it would have floated away and been lost into space long ago.

- The small planets hardly have any volatile elements, either, but that's because of their location. They're too close to the Sun. They are within the "snow line" surrounding the Sun that marks the rough boundary where the volatiles go from being gaseous on the inside to solid on the outside.

- Without much in the way of gases or volatiles, the atmospheres of the small planets are very thin. Our atmosphere on Earth is mainly nitrogen and oxygen, with trace amounts of other gases, such as water vapor, argon, and carbon dioxide. It's very important to us, but on a planetary scale, it's an extremely thin, nearly inconsequential layer, representing only a millionth of the mass of the planet.

The Compositions of Midsized Planets

- Are the midsized exoplanets—with sizes in between Earth and Neptune—rocky? Or gaseous? Or something else entirely? Most importantly, how can we tell the difference?

- Theorists build computer models of planets with different hypothetical compositions. The principle of hydrostatic balance—the idea that at any depth within the planet, the downward force of gravity is being balanced by the pressure force of all the surrounding material—can be used to solve for the structure of the planet: how the density and the pressure increase with depth.

- But to get a unique answer, they have to assume something about how much the material compresses when it is pushed on with a certain pressure and at a certain temperature. That relationship—between pressure, density, and temperature—is called the equation of state, and it depends on the material. Water is more compressible than rock, for example, and both of them are more compressible than iron.

- Theorists assume some composition for the planet, and then they use the equation of state for those materials and the principle of hydrostatic balance to arrive at the structure of the planet. Then, they can predict things; most importantly, if they stipulate a certain total mass for the planet, they can predict the size, and the diameter. The answer will depend on the assumed composition. Then, they measure the mass and the diameter, compare the results to all the different models, and see which one fits.

- This gives us a way, in principle, to distinguish between the possibility that these midsized planets are super-Earths or mini-Neptunes. Measure their masses and sizes. Measure their densities and compare them to the theoretical models corresponding to scaled-up rock-iron planets or shrunken ice giants.

- But why are we so sure that those are the only possibilities? Why does it have to be either a super-Earth or a mini-Neptune? Many theorists in this field have posed similar questions. They've tried to get creative and anticipate some other possibilities.

- The one that's been discussed most frequently is a water world. The idea is that it could be like Uranus or Neptune, rich with water, methane, and ammonia but without any hydrogen or helium. A water world would be quite different. There would be a planetwide ocean on top of a thick layer of ice, hundreds of kilometers deep, sitting on top of the rocky mantle.

- Another, more speculative possibility is a carbon planet. Planets in a carbon-rich star system could have a totally different structure than in the solar system.

- With all these theoretical possibilities, how are we going to figure out what's really out there? The first thing is to measure the mass and the size of the planet. In fact, you really want to measure the sizes of hundreds of planets, over a range of masses. That's because different compositions lead to different predictions about the relationship

between mass and size. Gas planets have lower densities than water worlds, which have lower densities than rocky planets.

- But with just the mass and size, there are too many possibilities. How are you going to tell apart a water world, a carbon world, and a regular rocky world that happens to have a thin layer of hydrogen and helium? They could all have the same density.

- There is another way, and that's the atmosphere. A water world's atmosphere would be completely dominated by water. If the planet were rocky with a layer of hydrogen and helium, the atmosphere would extend up to relatively high altitudes, compared to the much thinner atmosphere of a normal earthlike planet.

- So, we need hundreds of measurements of planet masses, sizes, and atmospheres. How are we going to do that? The answer is transits. When a planet transits its parent star, there's some hope of measuring the planet's mass, radius, and atmosphere.

Suggested Reading

de Pater and Lissauer, *Planetary Sciences*, chap. 6.

Rothery, McBride, and Gilmour, eds., *An Introduction to the Solar System*.

Ryden and Peterson, *Foundations of Astrophysics*, chaps. 9–10.

Seager, ed., *Exoplanets*, chap. 17.

Questions to Consider

1. Will we ever be able to be confident in our knowledge about the interiors of planets, given that we cannot directly observe them?

2. Consider a rocky planet that is twice the size of Earth. Would there be any special challenges or fundamental obstacles to life arising on such a planet?

Transiting Planets and the Kepler Mission

Lecture 11

In exoplanetary science, the research frontier has been steadily advancing toward smaller and smaller planets—away from the giant planets that were discovered in the earliest observations and toward planets as small as the Earth. In this progression, the greatest advances for the transit technique have come from new telescopes in space. In particular, the Kepler space telescope has made many sensational discoveries. The goal of this lecture is to explain the purpose, history, capabilities, and context of the Kepler mission.

High Precision

- To find a transiting planet, you need to monitor the brightness of thousands of stars for long, uninterrupted intervals of time as precisely as possible. The reason you need precise observations is that a transiting planet only blocks a small fraction of the starlight. The fractional change in brightness is equal to the square of the ratio of the planet's size to the star's size. For a giant planet around the Sun, that's 1%. For an Earth-sized planet, it's closer to 0.01%.

- There's no way you could detect such tiny brightness changes by eye. Even if you have perfect vision and years of stargazing experience, it's very difficult to sense any change in a star's brightness unless it's at least 10%.

- Instead, we use digital cameras. The technical term for the crucial part of a digital camera—the part that actually detects the light—is a charge-coupled device (CCD). It's based on a piece of purified silicon.

- Like other semiconductor materials, silicon has the wonderful property that when you shine light on it—when photons hit the silicon—the electrons in the silicon can absorb that energy, and, crucially, the electrons retain that energy for a relatively long time. The electron gets stuck with the energy and can therefore be distinguished from all the normal electrons in the material.

- Furthermore, we can trap the energetic electron and force it to stay close to where the photon hit, using electric fields. We put tiny electrodes on the back of the silicon to create a grid of electric fields. So, whenever a photon comes in, it excites an electron in a certain square of that grid, and we can trap the energetic electron right there. Those little squares are going to be the pixels in the digital image.

- To make an image, we collect light with a telescope and focus it onto the silicon for a certain amount of time: the exposure time. All those photons from the star rain down on the silicon and knock loose electrons.

- Then, we cover up the silicon—we close the camera shutter—and arrange for all those electrodes on the back of the silicon to count the energetic electrons within each pixel and send the results to a computer. Then, the computer makes an image. The brightness of each pixel in the image is set according to the number of electrons that were collected from the corresponding location of the silicon wafer.

- It seems easy to monitor the brightness of a star: We just make image after image with our CCD every minute, for example. Then, we count the number of electrons in each image. If we see that it goes down, the star must have gotten fainter.

- But there are other things that could cause the electron count to go down. If a cloud passes in front of the star, then the images will suddenly go blank. And even when the sky looks clear, slight changes in temperature or humidity affect the air's tendency to scatter starlight, which can change the apparent brightness of the star by a few percent. These effects swamp the smaller signal of an exoplanet transit.

- You can try to correct for these effects by monitoring many stars together. The hope is that the brightness variations caused by the atmosphere will be the same for all the stars. In contrast, an exoplanet transit will cause only 1 star to get fainter. That's the idea

of differential photometry: You ignore brightness changes common to all stars and only pay attention to changes specific to 1 star.

- That works pretty well and lets you measure brightness changes down to about 0.1%—a big improvement. But it's difficult to go further. Even differential photometry doesn't work perfectly, because the atmosphere doesn't affect all stars in exactly the same way. The effect of the atmosphere has limited the precision of photometry using Earth-based telescopes to about 0.1%. That's not good enough to detect the transit of an Earth, an effect of 0.01%.

- A good reason to go into space is to go above the atmosphere, which corrupts our brightness measurements. But building a space telescope doesn't solve all our problems. There's always a limit to the precision we can achieve, even in space. The reason is because of 2 of the deepest principles of physics: quantum theory and thermodynamics.

- The connection to quantum theory is that the energy in light comes in discrete little chunks: photons. Light has both wavelike and particle-like properties. In a CCD, a photon, a particle of light, hits the silicon and knocks loose an electron. The CCD counts photons.

- Next comes the connection to thermodynamics. Stars emit light because they're hot. Heat is the energy associated with random motion of atoms and ions on the microscopic level. Thermodynamics tells us that whenever something is emitting light because of random motions, the intensity of the light fluctuates randomly.

- Even if nothing is happening to the star and even if there's no atmosphere absorbing photons, the detected number of photons will jiggle around the average value. This unavoidable natural phenomenon is called photon noise.

- There's no way to avoid photon noise, whether you're using an Earth-based telescope or a telescope in space. But we can use a bigger telescope. We collect more light with a bigger eyeball. That

improves the ultimate precision of our measurements, by reducing photon noise.

- Photon noise is proportional to the distance to the star divided by the diameter of the telescope times the square root of the star's luminosity times the exposure time. If you want precise measurements of stellar brightness, you can use a bigger telescope or a longer exposure time, or you can look at more luminous stars or stars closer to the Earth. These calculations about photon noise apply to both Earth and space telescopes.

Lots of Observing Time and Stars

- In addition to needing precise observations, the second requirement for a transit survey is that you need to observe stars for a long stretch of time. The reason is that transits only occur once per revolution of the planet—once every 3 days for a hot Jupiter and once a year for an Earth twin.

- Depending on what kind of planet you're looking for, the campaign has to last anywhere from weeks to years, or more. And the transits themselves only last a few hours, so you have to be observing continuously during all those weeks or years to make sure you don't miss any transits.

- This is very difficult to do with telescopes on the ground. The Sun is up for half the time, so from a given site, you'll never be able to observe the night sky continuously. It's also impossible to avoid interruptions due to bad weather.

- In space, the sky is always black. You can stare at a given star for weeks or years at a time, in principle, without interruption. In practice, it's not quite so simple. It depends critically on where in space your telescope is sitting.

- If it's in an orbit that tightly hugs the Earth, the easiest place to get to, then it's not so great. In a low-Earth orbit, a spacecraft goes around the Earth once every 90 minutes. For half of that time, the

Earth itself is probably blocking the view of your star, and there's also lots of stray light from the Earth that gets into your telescope.

- That's one reason we can't use the Hubble Space Telescope: It is in a low-Earth orbit, making it a lousy place for precise brightness measurements. Another reason is that we can't take over the Hubble for several years; it's the most popular telescope in astronomy.

- The third requirement for a transit survey is that you need to observe thousands of stars, or more. The reason is that most planets do not transit; they orbit around their star but never cross right in front of it. For transits, you need a special coincidence. Only 10% of hot Jupiters transit; only 0.1% of Earth twins transit.

- This is another reason we can't use Hubble. It has a tiny field of view, so it's not very practical to survey a lot of stars. You want a telescope with an unusually wide field of view that can measure lots of stars at the same time.

The Kepler Space Telescope

- The Kepler space telescope is a wide-field telescope that is far away from Earth, where it can view the stars without interruptions and without stray light. It was conceived in the early 1980s by a scientist named William Borucki, who works at NASA's Ames Research Center in California.

- In 1999, astronomers conducted the first space-based search for transiting planets. It was a survey with the Hubble Space Telescope. Astronomer Ron Gilliland overcame the limitations of Hubble by restricting the search to hot Jupiters with orbital periods of a few days, so he didn't need to take over the telescope for years. He also figured out a way to observe thousands of stars even within Hubble's tiny field of view: He looked at a globular star cluster, which has millions of stars.

- Globular clusters are convenient targets for a transit survey—all those stars packed tightly into a small area of the sky. Ron Gilliland

and his colleagues used Hubble to stare at a globular cluster called 47 Tucanae for 8 days straight. Based on what was already known about hot Jupiters, they calculated that they should have found about 30 transiting hot Jupiters. But, in fact, they found 0.

In the 2000s, when the Kepler space telescope was built, it had the world's biggest camera for a civilian spacecraft.

- In 2000, Bill Borucki's proposal was approved by NASA, and the engineers got to work building the Kepler space telescope, named after the scientist who worked out the basic laws of planetary motion. It has what was at the time the world's biggest camera for a civilian spacecraft. The telescope has a wide field of view, and the telescope mirror is big enough to reduce the photon noise to the right level—good enough to detect the transit of an Earth, a signal of 84 parts per million.

- The whole Kepler project cost about $640 million. The telescope took a long time to build. In fact, in the time it took to build, a smaller space telescope named Corot was launched by a group of European countries and conducted its own transit survey. It was not nearly as capable as Kepler, but it did find a few hot Jupiters and a smaller planet even before Kepler was launched.

- Finally, in 2009, the Kepler space telescope was launched into space from Cape Canaveral. The Delta II rocket that carried Kepler into space was powerful enough to take it well beyond a

low-Earth orbit; in fact, it escaped the Earth's gravity altogether. The telescope is on its own private orbit around the Sun, gradually drifting away from the Earth.

- For 4 years, it stared nearly continuously at a particular patch of the sky, within the constellations of Cygnus and Lyra. It had a spectacular run, finding thousands of transiting planets, along with a host of other astronomical phenomena that could be studied in unprecedented detail.

- In particular, Kepler confirmed the claim from the Doppler surveyors: The data showed that at least 40% of sunlike stars have planets with orbits shorter than a year and sizes in between those of Earth and Neptune. And they very frequently come in groups of 2, 3, 4, 5, or more planets, all orbiting the star together in small, compact systems.

- The solar system does not represent the universal template for planetary systems around the galaxy. We still don't know how common or rare systems like the solar system are, but we do know that nearly half of other stars have planetary systems very unlike the solar system.

Suggested Reading

Bhattacharjee, "Mr. Borucki's Lonely Road to the Light."

Gilliland, et al, "A Lack of Planets in 47 Tucanae from a Hubble Space Telescope Search."

Lemonick, *Mirror Earth*.

Questions to Consider

1. How might life have been different on Earth if the Sun were part of a globular cluster with millions of nearby stars?

2. Does the detection of earthlike planets seem important enough to justify the $640 million cost of the Kepler mission?

Compact Multiplanet Systems

Lecture 12

The Kepler space telescope was sent into space to find transiting earthlike planets. The primary goal of the Kepler mission was to establish how common or rare are planets similar to the Earth. But in some ways, some of the other discoveries Kepler made are more interesting than the discovery of earthlike planets. The first of those discoveries, and the topic of this lecture, is the widespread existence of compact multiplanet systems, in which multiple planets interact in complicated ways.

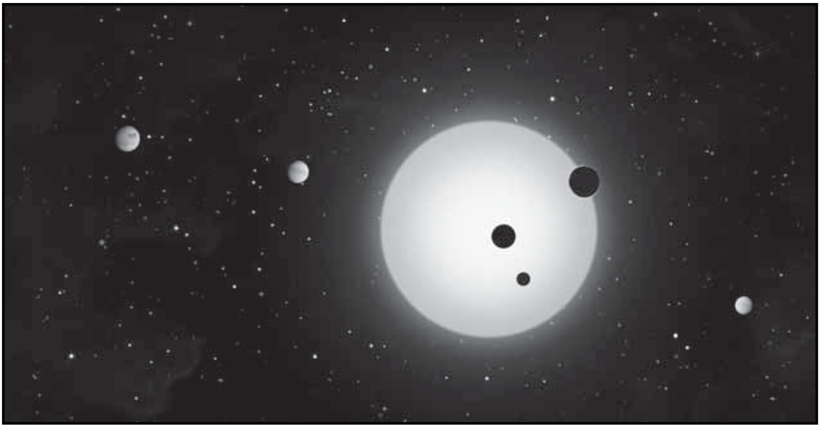
The Discovery of Compact Multiplanet Systems

- In 2008, the Doppler surveys revealed a population of planets in between the Earth and Neptune in size: the so-called super-Earths or mini-Neptunes. But there was a legitimate concern over how many of those detections were real. The signals were weak, just barely poking out above the noise level of the measurements.

- Kepler put those concerns to rest. Within a few months after the first data became available, the Kepler team was amazed by how many stars had transiting super-Earth and mini-Neptune planets. Even more amazing was how many stars had more than 1 such planet—there were scores of systems of multiple transiting planets.

- A good example is the planetary system known as Kepler-11. At its center is a star like the Sun, and there are at least 6 planets circling around, ranging in size from about 1.8 to 4.2 times the size of the Earth. All 6 planets have orbital periods shorter than 120 days, and Kepler's third law tells us that a short period implies a small orbit, so these planets are tightly packed around the star.

- The Kepler mission found hundreds of these compact multiple-planet systems. Nearly a quarter of the stars that showed any transits at all also showed transits of more than 1 planet. All of these systems are



Kepler-11 is a compact multiplanet system.

more crowded than the solar system, and there is a preponderance of planets in between the sizes of Earth and Neptune.

- This discovery led to a major change in perspective. Before Kepler, we were nearly blind to planets smaller than Neptune. The higher precision of Kepler gave us a less myopic, more representative view of the planets that are really out there.

- The ubiquity of all these midsized planets is fascinating and mysterious. It raises the question of whether the solar system is actually anomalous, rather than being ordinary, as scientists had been assuming all along. It also raises the question of how these compact multiplanet systems came to be. How did they form in such tightly packed orbits?

- Current thinking is that they didn't form in such tight orbits—because the total mass of planets is simply too large to have plausibly accreted from the material in such a small area. Instead, maybe the planets formed farther out from where we see them today and then somehow moved inward to take up their current positions. Maybe this movement occurred because of gravitational

interactions with the protoplanetary disk—the theory of planet migration, a possibility discussed for hot Jupiters.

- But there are problems with this theory. Namely, why doesn't the hot Jupiter spiral all the way into the star and get destroyed? For compact multiplanet systems, the problem seems even worse: How could all these planets spiral into these tight configurations and somehow avoid colliding or gravitationally throwing each other around?

- Many of these systems are on the edge of stability. What process caused all the orbits to shrink a lot but not so much that they interfered with each other? We don't know, so we're continuing to examine these compact multiplanet systems in every way we can, looking for clues.

Are These Systems Flat?

- One important question is whether or not these systems are flat: Are the planets' orbits all aligned, like the orbits of the solar system planets, or are they whirling around the star in more random directions?

- Because all the planets are all transiting, then don't all the orbits have to be in the same plane, so that they all cross in front of the star? Actually, no. It's not a foregone conclusion that the compact multiplanet systems are flat.

- Just because 2 planes are both parallel to the same line, they need not be parallel to each other. So, transits alone cannot tell us whether a planetary system is flat. However, there are a few systems where we have gained some extra information that does allow us to measure the angles between the orbits, and in those few cases the systems have all turned out to be flat.

- The most interesting case is a system called Kepler-89. It has 4 transiting planets, ranging in size from 1.5 to 9 times the size of the Earth, and orbital periods ranging from 4 days to 22 days. It's a

very compact little system. Evidence from Kepler-89 shows that the compact multiplanet systems are flat.

- There are also statistical arguments, based on the number of multiple-transiting systems that we've seen and the patterns in the durations of the individual transits, that suggest that the other systems are flat. And that, in turn, suggests that these compact multiplanet systems did form within a flat disk—the protoplanetary disk—and that there's probably no need to invent a new theory of planet formation to account for them.

- But there's still the problem of whether the planets "migrated" inward or not and why they're so closely packed. We're hoping to obtain another clue to this mystery by measuring both the sizes and the masses of the planets. Are they rocky planets? Ice giants? Water worlds? Gaseous planets? If we could tell, then we might learn something about when and where the planets formed.

- But the transit data only tell us the size of the planet. To get the mass, we usually need to follow up with Doppler measurements, to gauge the strength of the gravitational force between the planet and the star.

- This is where we run into a problem. The Kepler space telescope has a serious limitation: The stars it examines are relatively distant and, therefore, faint. Unfortunately, Kepler stars are mainly too faint for Doppler spectroscopy.

The Transit-Timing Method

- There is a sneaky way to measure the planet masses in these compact multiplanet systems. The planets in these systems are so close to one another that they exert substantial gravitational forces on each other. So, it's not just the star that's pulling on a planet—it's also the neighboring planets. This causes the planets' orbital motion to be slightly irregular.

- If there were just 1 planet going around the star, the transits would repeat on a perfectly regular schedule—for example, once every 20

days. But if there are other planets pushing and pulling it around, then the transiting planet is getting sped up and slowed down. This causes the transits to occur on a different, more complicated schedule. The transit might happen a few minutes or hours early, or late, depending on the recent history of all these pushes and pulls.

- The crucial thing is that the strength of those pushes and pulls depends on the masses of the planets: The more massive, the stronger the gravitational force. So, by observing the irregular timings of the transits, there's some hope of measuring the masses of the planets.

- This method, called the transit-timing method, was dreamed up by exoplanet theorists in 2005, even before the Kepler spacecraft was launched. We can use transit-timing variations to measure masses of planets and even to discover planets that are not transiting.

- Using this method, astronomers have measured the masses of a few dozen of the medium-sized planets in the Kepler systems. The results suggest that they're not rocky planets. They're too lightweight. Their densities are often like those of Uranus and Neptune, and sometimes as low as the gas giants—in fact, sometimes even lower.

- Many astronomers have questioned these results, but others are taking them seriously. They've even come up with a new name for this category of planets: Objects smaller than Neptune but less dense than Neptune are called gas dwarfs, to distinguish them from gas giants.

- This method works especially well when 2 or more planets are in a particular configuration: when the planets' orbital periods have a simple ratio of whole numbers, such as 2 to 1. At least a few percent of the multiplanet systems have these kinds of simple ratios, called resonances.

- There's an analogous concept in acoustics and music. When a piano string vibrates, the period of vibration—the time it takes to wiggle

back and forth—is what determines the pitch of the note. Shorter periods give higher pitches.

- When you have 2 strings whose vibration periods are in exactly the ratio 2 to 1, then those notes are an octave apart. They harmonize perfectly. If the periods are in the ratio 3 to 2, the notes also harmonize pretty well—that's a perfect fifth.

- Planets can harmonize, too. If the orbital periods have a 2-to-1 ratio, then every time the outer planet makes a complete revolution, the inner planet has made exactly 2 full revolutions, and the planets are right back in the same positions where they started. That means the pushes and pulls that the planets exert on each other will repeat exactly for every orbit of the outer planet.

- This resonance allows all of the disturbances of the orbits to accumulate and build up to large amplitudes. Without resonance, the pattern of pushes and pulls is essentially random from orbit to orbit, and the disturbances tend to cancel each other out. This is not so for resonant systems.

- The practical implication is that the resonant systems produce the biggest transit-timing variations. The variations can be not just minutes or hours but days for the most resonant Kepler systems. This is great because it means that we're able to measure those interactions very precisely and derive lots of information about the masses and orbits of the planets.

- Kepler found a few dozen of these special resonant planetary systems. They're rare, but they do seem to happen more often than you would think, if the periods were just random numbers. In contrast, none of the planets in the solar system are in resonance with each other, although some of the moons in the solar system are in resonance.

Suggested Reading

Carter, et al, "Kepler-36."

Seager, ed., *Exoplanets*, chap. 10.

Winn and Fabrycky, "The Occurrence and Architecture of Exoplanetary Systems."

Questions to Consider

1. The Kepler spacecraft found that 40% to 50% of stars like the Sun have a planet quite unlike any planet in the solar system: between Earth and Neptune in size with a period shorter than a year. What would be the implications if the solar system turns out to be a very unusual type of planetary system in the galaxy?

2. The historical development of science on Earth was closely connected to the desire to explain the regular motions of the planets. How might this history have differed if the solar system were as unpredictable as the Kepler-36 system?

Planets Circling Two Stars
Lecture 13

One property of the solar system that is essential and easy to take for granted is that it has only 1 Sun. Can you imagine a planet with 2 suns—a planet that orbits around 2 stars at the same time? Actually, you probably can; it's a familiar concept from science fiction. But does such a sight actually exist somewhere in our galaxy? Astronomers have been curious about this question—the subject of this lecture—for a long time.

Circumbinary Planets

- Our curiosity about whether there exists a planet that orbits around 2 stars at the same time is fueled by 3 factors. First, double stars—pairs of stars that orbit one another—are very common. We call them binary stars. About half of all the points of light in the sky are actually double stars. They orbit each other so closely that you need a telescope to tell there's more than 1 star.

- We also know of triple-star systems, quadruple-star systems, quintuple-star systems, and so on, but these are progressively rarer. Binaries, though, are everywhere. In some of them, the 2 stars hug each other tightly, actually touching each other. In others, the stars seem barely aware of each other, with orbital distances of tens of thousands of AU—that is, tens of thousands of times bigger than the Earth-Sun distance.

- If you look at young and relatively close binaries—less than a few million years old, with the stars separated by less than a few AU—you sometimes find a protoplanetary disk of material that surrounds both stars. So, there are many places where planets might exist around binary stars. There is a lot of potential real estate for so-called circumbinary planets, whose orbits surround 2 stars instead of 1.

- A second reason why it's important to check if circumbinary planets exist is that their existence raises some interesting theoretical

questions. One theoretical issue is stability. Could the planet's orbit be stable over billions of years?

- When you have 2 bodies orbiting one another, whether it's a planet going around a star or 2 stars going around each other, the orbit is definitely stable. The orbit has the shape of an ellipse, and that shape stays the same forever. But as soon as you have 3 bodies orbiting one another, there is usually no guarantee that the orbits will be stable. Certainly, they won't stay the same shape forever.

- For example, if there are 2 stars orbiting each other in a tight little circle and a planet on a larger elliptical orbit surrounding them both, neither the stars' orbit nor the planet's orbit will stay the same over time. The shifting positions of the stars will exert a complicated time-variable gravitational force on the planet that causes the planet's orbit to change, and the planet acts back on the stars to change their orbit.

- The changes can be divided into different categories. One effect is that the orbit twists around so that over time the long axis of the ellipse rotates in space. This is called apsidal precession. Another effect is that if the planet's orbit is not aligned with the stellar orbit, then the orbital planes will pivot around in space such that the motion draws out a cone. This is called orbital precession. In addition, the shape of the planet's orbit—the orbital eccentricity—will fluctuate with time.

- If the planet's orbit is too close to the stars to begin with, then all these different effects eventually cause the planet to approach one of the stars too closely, and the planet either gets flung out into deep space or engulfed by one of the stars. This is one aspect of the 3-body problem, the motion of 3 bodies under their mutual gravitational forces. The presence of 3 bodies is enough to create the potential for unpredictability and chaos.

- Exoplanet theorists have simulated a wide variety of different starting configurations and have discovered that as long as the ratio

of the 2 periods—the planet's orbital period divided by the stars' orbital period—is more than about 4 or 5, the planet is safe for millions of orbits or more.

- So, we don't expect to find circumbinary planets on orbits with periods shorter than 4 or 5 times the period of the binary star. And if we do find one, it would have to be on a rather special and seemingly fragile orbit that would probably be an important clue about how it formed.

- Another theoretical issue is planetesimal growth. Planet formation is supposed to be a bottom-up process, with tiny dust grains sticking together to make rocks, which glom together to make boulders and eventually planet-sized balls.

- One of the unsolved problems within this theory is the step when the rocks become on the order of a meter in size—the meter barrier. Simple calculations suggest that such objects are vulnerable to drag forces, which cause them to spiral down and fall into the star. So, we must be overlooking some physical process that allows real rocks to get past this meter barrier and grow into full-fledged planetesimals.

- There are theoretical ideas for how this might happen, but no good ways to test whether they are correct. Circumbinary planets might provide a test. If circumbinary planets do exist, they form within the protoplanetary disk that surrounds both stars. But this type of disk is a little different from the disks that surround isolated stars. In a binary, the moving stars cause gravitational forces on the disk that are always changing, and that stirs up the gas and the dust in the disk. It increases their random motions.

- The key question is whether planetesimal growth can actually proceed, despite all that constant stirring. The different theories for planetesimal growth make different predictions, in principle, for how robust the process is and whether it can happen in a circumbinary disk. If we do find circumbinary planets, we can rule out the theories in which planetesimal growth is a fragile process.

- In addition to the scientific reasons why we search for circumbinary planets, there is a third reason that is less scientific: long-lasting effects of our childhood addiction to science fiction. Many of the individuals who choose to become astronomers were raised on a diet of Isaac Asimov, Arthur C. Clarke, and George Lucas. With all that motivation, astronomers eagerly anticipated the discovery of circumbinary planets.

PSR B1620-26

- The first known circumbinary planet is a planet whose 2 parent stars are a pulsar and a white dwarf, residing within a globular cluster. A pulsar is a type of neutron star: the ultradense core that's sometimes created when a massive star collapses. Globular clusters have millions of stars packed into a densely populated space. A white dwarf is a tiny star that glows white-hot.

- A white dwarf is much smaller than a normal star; its diameter is closer to that of a planet. Normally, stars that small are relatively cool, glowing deep red or even infrared. But white dwarfs glow white-hot instead of red-hot, so they can't be regular stars. In fact, they're another type of dead star, like neutron stars, but in this case, the star that died is not a massive star—it's a more normal star, like the Sun. The white dwarf occupies only a millionth of the volume of the original star, but it still retains most of its mass, so it's nearly a million times denser than the original star.

- The first known circumbinary planet is called PSR B1620-26. The system is inside the closest globular cluster to the Sun, a cluster named Messier 4. It's a case where the planet was revealed by timing the arrival at the Earth of the radio pulses that are emitted by the pulsar. Through these timing measurements, it gradually became clear that the pulsar was moving around the center of mass of a 3-body system.

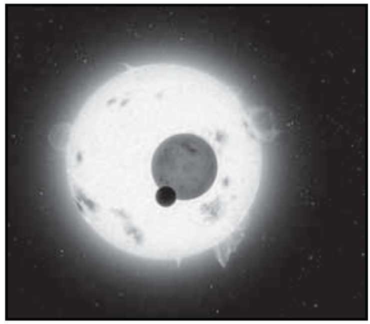
- One of the bodies is the pulsar itself. The second is a white dwarf that has a mass about 1/3 of the Sun's mass. The white dwarf and the pulsar are orbiting each other every 191 days. The third body

is the planet, whose properties can't yet be pinned down exactly, but it seems likely to have a mass a few times that of Jupiter and an orbit that goes around both the pulsar and the white dwarf every few decades.

- Just as the origin of the original pulsar planets is mysterious, so is the origin of the circumbinary pulsar planet.

Kepler-16

- For a long time after B1620-26 was discovered, there were no firm discoveries of circumbinary planets—just the occasional claim that turned out to be dubious or spurious. Then, in 2010, the Kepler team found the first unambiguous case of a circumbinary planet around a pair of normal stars. What made it unambiguous was that the planet transits the stars as it goes around both of them.



Kepler-16 is a system that consists of a circumbinary planet around a pair of normal stars.

- In this system, known as Kepler-16, both stars are relatively small: Their masses are 20% and 70% that of the Sun. They orbit each other every 41 days, at a distance of about 1/5 of an AU. Both stars are less luminous and cooler than the Sun, the small star especially so. The planet is about the size of Saturn and goes around both stars in a big circle every 229 days.

- The whole system is neatly aligned. Both orbits are lined up within a half of a degree, and the primary star is rotating in the same direction as the orbital motion. From our vantage point on Earth, we view the system nearly exactly side-on, so that the stars eclipse one another, and the planet transits across both of the stars, and we can detect all of these dimming events with the Kepler space telescope.

- The data fit perfectly with a model of a 3-body system interacting under the Newtonian laws of motion and gravity, leaving very little room for doubt that this is a genuine case of a circumbinary planet.

- After we fit all of the data with that simple model, we realized that there's another reason why circumbinary planets are interesting: We can measure the sizes and masses of all 3 bodies with unusually good precision. For Kepler-16, we know the dimensions of both stars to within 1%, and we know the dimensions of the planet to within a few percent. This is much better than the usual case of a planet around a single star, where the uncertainties in the sizes and masses are more typically 10% or 20%, or worse.

- The reason why circumbinaries offer such great precision is all of the 3-body effects, including apsidal precession, orbital precession, and changes in eccentricity. Even more importantly, there's the fact that the stars are moving around, so the eclipse times are not exactly periodic. All of those effects give us many additional things we can measure, beyond the usual things. And the more independent things we can measure, the more precise and confident we can be in the parameters of the model—which in this case are the masses, sizes, and orbits of the 3 bodies.

- Another interesting consequence of all the 3-body effects is that the planet's climate undergoes big annual swings, because the distance between the planet and each of the 2 stars varies so much with time.

- Since 2011, another 8 circumbinary systems have been announced, all based on data from the Kepler telescope. So, the current total is 10 circumbinary planets, and that total is likely to grow as the Kepler data are explored more thoroughly by both amateurs and professionals.

- It's a little early to draw any conclusion about how common circumbinary planets really are, but with at least 10 found from within Kepler's sample of about 2000 eclipsing binary stars, it seems likely that circumbinary giant planets are at least as

common as giant planets around isolated stars over the same range of orbital periods.

- This, in turn, suggests that the planetesimal growth process is very tolerant of the stirring and randomizing effects of the time-variable gravity produced by the stellar binary. In addition, all the known planets are outside of the limiting orbital distance for long-term stability; they all have periods that are at least a factor of 4 to 5 longer than the period of the stellar orbit.

Suggested Reading

Doyle, et al, “Kepler-16.”

Welsh and Doyle, “The Discovery of Planets with 2 Suns.”

Winn and Fabrycky, “The Occurrence and Architecture of Exoplanetary Systems.”

Questions to Consider

1. Are there any serious challenges or fundamental obstacles to life arising on a planet with 2 stars in its sky?

2. What other types of planets drawn from science fiction have yet to be discovered in reality?

Lava Worlds

Lecture 14

In science, it's often interesting to think about the most extreme cases of any phenomenon. This lecture will try to answer the following question: What is the smallest possible orbit for a planet? First, you will learn about the relevant physical laws that might limit how short a planet's "year" can be, and then you will learn about some of the planets with the shortest periods and smallest orbits that have ever been discovered—the so-called lava worlds.

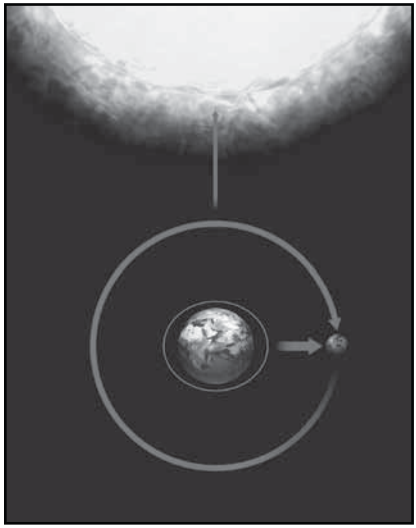
The Smallest Orbits and Shortest Periods

- The first and most obvious limit on how small a planet's orbit can be is that it needs to be outside the surface of the star—no planet would last very long orbiting inside a star. So, the radius of the orbit has to be bigger than the radius of the star. That same requirement leads to a minimum possible orbital period, because Kepler's law tells us that the orbital distance and orbital period are related: $P^2 = a^3/M$, where P is the planet's orbital period in Earth years, a is the orbital distance in AU (1 AU is the Earth-to-Sun distance), and M is the mass of the star relative to the Sun.

- For a sunlike star, the minimum orbital period is 2.8 hours. Shorter than that, and the planet would be dipping its toes into the hot plasma of the Sun's photosphere. In fact, bad things would probably happen to the planet even somewhat farther out than that.

- There's also the danger posed by tides. Tidal forces—the stretching force that occurs because the star's gravity pulls harder on the near side of a planet than it does on the far side of the planet—try to stretch the planet. If there were nothing to oppose the tidal forces, they'd tear the planet into pieces, pulling the material from the near side into shorter and faster orbits and pushing the material on the night side into more distant, slower orbits.

- Usually, though, there is something opposing the tidal forces: the planet's own gravity, which holds everything together. And, usually, the tidal force is small compared to the planet's own gravity. So, the tidal forces produce interesting but harmless effects, such as the ebb and flow of ocean tides on the Earth. But as a planet gets closer to a star, at some point the tidal force overwhelms the planet's own gravitational attraction, and the planet will be torn apart.



The tidal forces on Earth produce the ebb and flow of ocean tides.

- This is called the Roche limit, named after mathematician Édouard Roche, and it refers to the smallest orbital distance for which the planet's own gravity can oppose the star's tidal forces. To be more precise, the Roche limit is the minimum orbital distance compatible with hydrostatic balance within the planet.

- Hydrostatic balance is the condition in which the weight bearing down on each layer of a planet is balanced by the pressure exerted by the material in the layer, which is being compressed. So, the gravitational force balances the pressure, and the planet is stable. That's the physical principle we use to help us guess what kind of material is inside planets and how it changes with depth. When there are tidal forces, too, for hydrostatic equilibrium to hold, we need there to be a 3-way balance between the planet's own gravity, the pressure, and the tidal forces.

- To figure out where the Roche limit is, we need to know something about what the planet is made of. Denser planets are more resistant to tidal forces than lighter, puffier planets. In fact, the minimum orbital period obeys a simple law: It's equal to about 12 hours divided by the square root of the planet's density, measured in grams per cubic centimeter.

- So, orbits cannot be arbitrarily small and their periods cannot be arbitrarily short because the orbit has to be outside the stellar surface as well as outside the Roche limit. In addition, close-in planets face other dangers. One of them is tidal orbital decay. This is a long-term consequence of tidal forces.

- Even if the planet is outside the Roche limit, the tidal forces cause the material to flow around the surface of the planet or within its interior, and the friction that inevitably accompanies those motions converts some of the planet's orbital energy into heat. The same thing happens on the star: The star feels tidal forces from the planet, and that causes the plasma within the star to flow around and dissipate energy. Those energy losses cause the planet's orbit to shrink, and eventually the planet is swallowed up by the star.

- This process is inevitable. But how long does it take? This is a complicated physics problem. In fact, nobody has yet managed to perform this sort of calculation from first principles. It turns out that we don't have a good quantitative theory for exactly how the sloshing motions of the tides get converted into heat.

- Even though we don't have a rigorous theory, we can simply observe the effects of tides in binary stars, where the tides are stronger and produce bigger effects, and based on those results, we can make educated guesses about how long it takes for a planet to suffer tidal orbital decay and fall into a star. For a typical hot Jupiter, our best guess is 40 trillion years. If this is correct, hot Jupiters don't need to worry about tidal orbital decay.

- Another peril of being a short-period planet is atmospheric escape. Because the planet is so close to the star, the atmosphere might heat up to several thousand degrees. Such hot gas is going to expand, causing the planet's atmosphere to puff up. If this gets out of hand, the planet will be so puffy that the outer layers will escape into space.

- This, too, is a difficult physics problem. There's no reliable theory that tells us exactly what to expect, but it does seem likely that there's going to be some maximum amount of heating compatible with a gaseous atmosphere. So, if the orbit is too small, a gas giant planet would lose its outer layers and shrink—and a smaller, solid planet might become an airless ball of rock and iron, like Mercury.

The Shortest-Period Planets

- Our best detection techniques are most sensitive to short-period planets. The Doppler signal is bigger, transits are more likely, and it's easier to observe many orbital cycles and confirm it's really a planet. So, we've learned a lot about the shortest-period planets.

- How hot are the hottest hot Jupiters? The results are interesting. We've discovered a total of 87 hot Jupiters with periods between 2 and 4 days. But if we ask how many have even shorter periods, we find fewer. Between 1 and 2 days, the answer is only 26, and below 1 day, there are only 4. As the period gets shorter than about 2 days, giant planets become increasingly rare.

- The shortest period known for any giant planet is 19 hours. For gas giants, the data indicate that the shortest possible period for a giant planet is probably not much less than 19 hours. That's interesting because it's outside the Roche limit, which is about 12 hours. So, there must be something else that prevents gas giant planets from existing between 12 and 19 hours—maybe it's tidal orbital decay, or atmospheric escape. It's not yet clear which one is more important, but we might be able to figure it out in the relatively near future.

- What about smaller planets? Before the era of the space-based transit surveys, we were nearly blind to planets smaller than Neptune; the signals of Earth-sized planets were simply too small to detect. This was true even for short-period planets, despite all the practical advantages of searching for planets with short periods.

- The space missions gave us our first good look at small planets in short-period orbits, and right away they found a few small planets with periods shorter than 1 day. Found by the European space telescope called Corot, Corot-7b is a planet about 1.6 times the size of the Earth with an orbital period of only 20.5 hours. Found by America's Kepler mission, Kepler-10b is 1.4 times the size of Earth, and its orbital period is about 20 hours. Both are in that new and interesting size range between 1 and 4 Earth radii, and both have "years" that last less than 1 Earth day.

- Researchers identified about 100 small planets with periods shorter than 1 day, and the data suggests that about 1 out of 500 sunlike stars has a planet with a period shorter than 1 day. All 100 of the new planets had sizes smaller than 2 Earth radii—half of Neptune's size.

- In theory, gas giant planets should be more vulnerable to being destroyed at short periods, due to tidal decay and atmospheric evaporation, and this is empirical evidence that at the very shortest periods, you find many small planets but very few gas giants.

Lava Worlds

- Kepler-78b is an Earth-sized planet that's special in 2 ways: The period is only 8.5 hours, and the star happens to be unusually close to Earth for a Kepler star, so the level of photon noise is relatively low. At the present time, Kepler-78 is the smallest planet for which we have direct measurements of its mass and size: It's just a little bigger in both dimensions than the Earth.

- Kepler-78b is extremely close to its sunlike parent star. Its orbital radius is only about 3 times the radius of the star itself.

- The surface temperature is predicted to be as high as 5000° Fahrenheit. That's hot enough to melt almost all known minerals, so the top layer of the planet is most likely completely molten, creating a massive roiling ocean of lava. For this reason, this new class of planets, with ultrashort periods and sizes comparable to Earth, sometimes are called lava worlds.

- Kepler-78b almost certainly does not have an atmosphere—at least not one made of nitrogen and oxygen. That kind of atmosphere would quickly escape. Theorists have hypothesized that the only plausible atmospheres for these types of planets would be composed of gaseous iron. It's hot enough for iron to vaporize off the surface and exist as a metallic haze, blanketing the planet.

- An 8.5-hour period is pretty spectacular, but that doesn't seem to be the shortest period that a planet can have. The record holder so far is a system called KOI 1843, which has a planet 40% smaller than the Earth and an orbital period of only 4.2 hours.

- The planet is close enough to the star to be encroaching on the Roche limit. According to calculations, the planet around KOI 1843 has to be denser than Earth, so if it's made of the same basic ingredients, rock and iron, then it must have a larger fraction of iron than the Earth does. That and the planet's small size mean that it might resemble Mercury more than the Earth.

Suggested Reading

Rappaport, et al, "Possible Disintegrating Short-Period Super-Mercury Orbiting KIC 12557548."

Ryden and Peterson, *Foundations of Astrophysics*, section 4.3.

Sanchis-Ojeda, et al, "A Study of the Shortest-Period Planets Found with Kepler."

Questions to Consider

1. This lecture was concerned with planets with record-holding short orbital periods. Can you think of other properties of a planet for which it would be interesting to know the most extreme possible limits?

2. Why might it be easier to calculate the eventual fate of a close-in planet than to calculate the amount of time that it takes to reach that fate?

Earthlike Planets

Lecture 15

Our interest in earthlike planets is driven by the desire to find planets suitable for life, and then to actually search them for signs of life—to find some company within the vast realms of space or to find out that we're alone. In this lecture, you will learn what constitutes an earthlike planet, and you will be introduced to a concept known as the habitable zone. In addition, you will be given a progress report on our search for such planets.

Basic Criteria for Life on Earth

- Which specific qualities of the Earth are most important, in comparison to other planets? This is a topic of ongoing debate. At the moment, the consensus is that for a planet to be potentially habitable, it should have a solid surface, it should orbit a star similar to the Sun, and its orbital distance should be similar to the Earth's, so that the planet's surface is heated by the star to about the same temperature as Earth.

- Specifically, we want the surface temperature to be in the range for water to exist as a liquid. That's the key criterion that qualifies the planet as not just earthlike but also potentially habitable. All life on Earth needs liquid water, and it's clear from the fossil record that life on Earth got started in the oceans. Liquid water seems to be a unifying principle for life on Earth.

- Another unifying principle is carbon. All life on Earth is based on the chemistry of carbon-based molecules: proteins, DNA, carbohydrates, etc. So, why are we so intent on looking for water instead of carbon?

- Carbon is everywhere. It's one of the most abundant elements in the galaxy. So, while carbon might be crucial for life, there's no shortage of it. That means that requiring carbon is not a helpful search criterion; it doesn't narrow down the possibilities.

- Water is also widespread throughout the galaxy, but liquid water is rare. Water is only liquid over a restricted range of temperature and pressure. For the pressure that prevails on Earth's surface, the temperature range for water to be a liquid is 32° to 212° Fahrenheit, or 0° to 100° Celsius. This narrows down the possibilities a lot. Planets too close to their stars will be too hot: Any water will be a vapor. And for planets too far away, all the water will be ice.

- How sure are we about the singular importance of liquid water? It's possible that it's critical for life as we know it, but on some other planet, things might work differently in ways we have not yet imagined. Nevertheless, it does seem like the best thing to try first.

- We can make some general arguments for why liquid water is important. For one thing, liquids seem like better bets than solids or gases. In a solid, nothing is free to move. It would be difficult for an organism to gather resources or reproduce inside a solid. A gas has the opposite problem: It's too easy for molecules to get diluted and tossed around by pressure and gravity. Liquid seems to offer the right combination of some freedom of movement while still allowing for the possibility of local concentrations of key chemicals.

Life on Earth got started in the oceans, and liquid water is needed by all life on Earth.

- Water is an especially good solvent for carbon-based reactions. The other 2 most common liquids in the solar system are methane (CH_4) and ammonia (NH_3), which are small molecules like water (H_2O), but with carbon or nitrogen replacing the oxygen. The problem is that they're both liquid at much lower temperatures than water, and that slows down chemical reactions to a crawl, giving the edge to water in the evolution of the chemistry of life.

- Liquid water is probably not sufficient for life; there are probably other ingredients that are just as essential. Some have argued that in order to be truly habitable, a planet needs to be geologically active, with volcanoes and continental drift, similar to what we have on Earth. In addition, maybe a habitable planet requires adequate protection from the star's dangerous ionizing radiation. Some have even argued that having a massive moon is crucial for life. Are all these things essential for life on other planets?

The Habitable Zone

- While eventually we might want to know whether a planet has plate tectonics, a large moon, a magnetic field, and an ozone layer, for the moment, it makes sense to simply look for planets with a solid surface and the right temperature for liquid water. That's what we'll consider a potentially habitable planet.

- We want the planet to have a solid surface—a platform for the liquid water to form oceans. This excludes gas giants like Jupiter and Saturn and also gas-rich planets like Neptune and Uranus. Based on our current measurements of the sizes and masses of exoplanets, to have a solid surface, an exoplanet should be no more massive than around 6 times the mass of Earth and no bigger in diameter than about twice the size of Earth. That's because planets with larger dimensions always seem to have thick gaseous atmospheres, so the surface would be smothered at an extremely high pressure, or there could be no surface at all.

- When the Sun is overhead, the Earth receives radiation from the Sun amounting to 1370 watts of power per square meter. We call

that number the flux of solar radiation. The flux varies as the inverse square of the orbital distance.

- The Sun is emitting a certain amount of power in all directions—luminosity (L), given in a certain number of watts. A planet intercepts some of that power, at a distance a away from the star. By the time the Sun's radiation reaches a distance a, all that luminosity has been spread out over a giant imaginary sphere, which has a total surface area of $4\pi a^2$. The flux, the power per unit area, is $L/(4\pi a^2)$.

- If we want to figure out the allowed range of orbital distances for a potentially habitable planet, first we need to figure out what range of fluxes will heat the surface to a temperature compatible with liquid water. Then, we can use the inverse square law to convert that into a minimum and maximum orbital distance. These calculations eventually lead to the range of orbital distances within which a planet with a solid surface would be potentially habitable—the so-called habitable zone around the Sun.

The Search for Earthlike Planets

- Each planet-finding technique is sensitive to different kinds of planets; each one has a sweet spot where it is especially effective. The Doppler method favors massive, short-period planets. The transit method prefers large-diameter planets and requires the orbit to be oriented in a special way. The astrometric method favors massive planets in very distant orbits. Two other methods, microlensing and direct imaging, also have their sweet spots at large orbital distances.

- The habitable zone is not the sweet spot of any of these techniques. It's too far from the star for the Doppler and transit techniques and too close to the star for the others. So, it's a struggle to find Earth-sized planets in the habitable zone with any technique.

- The first opportunity we had to overcome this difficulty was the Kepler transit survey. Detecting Earth-sized planets in the habitable

zones of sunlike stars was the primary goal of the Kepler mission. Everything was designed around that goal: the selection of target stars, the size of the telescope, the precision with which it could measure brightness changes, and especially the duration of the mission. It had to last at least 3 years so that 3 transits could be detected for a planet in the habitable zone, which would have a period of around 1 year.

- If all went well, Kepler would reveal how common, or how rare, earthlike planets are. The way the mission planners framed it, Kepler would measure the so-called occurrence rate of earthlike planets: the average number of such planets per star.

- Certainly, Kepler told us a lot about the occurrence rate of planets interior to the habitable zone and planets that are somewhat larger than Earth—planets that are easier to detect with the transit method. But finding planets as small as Earth on orbits as distant as the habitable zone has been difficult, despite having collected data for more than 4 years before the mission ended. Only a few candidates have been reported.

- Part of the problem is that the brightness data are not quite as precise as had been anticipated. It's not clear why. It could be a problem with the camera or with the software that's used to analyze the data—or it could be the fault of the stars themselves. Some have argued that the stars are flickering randomly in brightness by more than anyone expected, producing extra noise in the data.

- Another problem is that in order to know whether a planet is Earth-sized and in the habitable zone, you need to know a fair amount about the star. The transit signal tells you the relative size of the planet and the star, but to figure out the actual size of the planet and compare it to Earth, you need to know the actual size of the star—and the stars that Kepler looks at are faint, anonymous stars, hundreds or thousands of light-years away. In many cases, their sizes are uncertain by 30% or more.

- Likewise, to know whether a planet is in the habitable zone, you need to know the luminosity of the star. The boundaries of the habitable zone depend on the flux received by the planet, which is equal to the star's luminosity divided by $4\pi d^2$. So, we need a good measurement of luminosity, and for these anonymous stars, we often don't know it to better than 50%.

- In principle, we could use our best ground-based telescopes to stare at these stars, measure their spectra, and derive better estimates of their sizes and luminosities—but that takes lots of time on telescopes that are always oversubscribed with all the possible stars and galaxies that someone wants to stare at.

- At the moment, the best we can do is perform coarse statistical analyses, hoping that our errors in the sizes and the luminosities of these stars will tend to cancel each other out, and make mild extrapolations from the occurrence rates of nearly Earth-sized planets, which are nearly but not quite in the habitable zones of sunlike stars.

- When we do those things, we naturally introduce a lot of uncertainty. The best current estimates for the occurrence rate of earthlike planets ranges from around 2% to 20%. The wide range reflects the varied problems, which are in addition to the ambiguities in defining the exact boundaries of the habitable zone.

- Before Kepler, any estimates of the occurrence rate were little more than wild guesses. It could have been 0.001, with earthlike planets rarer than hot Jupiters, or it could have been 3, with the Sun being unusual in having only 1 habitable planet. Kepler has at least made clear that the truth is in the middle, in the neighborhood of a few percent or a few tens of percent. That's good progress for a number that people have been wondering about for centuries.

- But how will we make further progress? One way is to continue analyzing Kepler data and gaining a better understanding of the

stars Kepler observed. This will be a slow process that will unfold over 3 to 5 years.

- We would also like to find earthlike planets around stars closer to Earth. For practical reasons, Kepler targeted stars hundreds of light-years away, but it would be nice to search the nearest and brightest stars. We know so much more about our neighboring stars than we do about all those anonymous strangers that Kepler observed.

- Finally, we are seeking such planets around sunlike stars, but to what degree does the star have to be exactly like the Sun? What if the star is not sunlike at all? If we're willing to entertain the idea that habitable planets can exist around stars that are much smaller and less luminous than the Sun, then we have a shortcut to finding earthlike planets in the habitable zone.

Suggested Reading

Kasting, Whitmire, and Reynolds, "Habitable Zones around Main Sequence Stars."

Petigura, Howard, and Marcy, "Prevalence of Earth-Size Planets Orbiting Sun-Like Stars."

Seager, "Exoplanet Habitability."

Questions to Consider

1. What are the most important properties that a planet must have to qualify as "earthlike"?

2. Some exoplanets have very thick hydrogen atmospheres that can produce extremely strong greenhouse effects. Does this mean that we should regard the habitable zone as extending out to arbitrarily far distances from the star?

Living with a Dwarf Star

Lecture 16

The Sun is often said to be a typical star, just one out of hundreds of billions of stars in our galaxy. In fact, the Sun is somewhat larger, more massive, and more luminous than the average star. Smaller stars are more widespread. The most common type of star is a little less than half the size and mass of the Sun, and its energy output is only 1/20 of the Sun's. These little stars are sometimes called red dwarfs, but astronomers usually refer to them as M dwarfs, where the "M" refers to the star's spectral type. M dwarfs are the subject of this lecture.

M Dwarfs

- Astronomers use an antiquated method for classifying stars. The scheme is based on examining the spectrum of a star: spreading out the light into a rainbow, looking at all those dark absorption lines, as well as how dark and how wide those lines are. From hottest to coolest, the stars are O, B, A, F, G, K, M, L, T, and Y. That's the spectral sequence.

- The Sun is a G star. The most common type of star is an M star, which is cooler than the Sun, 2 places farther in the spectral sequence.

- A star's temperature, mass, and size are all closely related. Hot stars are massive and big; cooler stars are smaller and less massive. Some stars, called giants, are relatively cool and have medium masses, but their diameters are enormous—10 or 100 or 1000 times bigger than the Sun. They're huge, bloated stars.

- An M star could be a sunlike star, but it could also be a giant. To specify what kind of star you're dealing with, you need to give not only the spectral type, but you also have to say whether or not it's a giant. If it's not a giant, we call the star a dwarf. The Sun is a G-type dwarf.

- Even though M dwarfs are the most common type of star in the galaxy, they are so faint that we can only see them if they're very close to the Earth, whereas we can see the more luminous G dwarfs out to much greater distances. Because luminous stars can be seen to much greater distances, they're overrepresented in the visible sky.

- Because an M dwarf is so much cooler and less luminous than the Sun, you have to put a planet closer to an M dwarf for it to receive the same flux as a planet around a G dwarf. That means the habitable zone of an M dwarf occurs at shorter orbital distances compared to the habitable zone of the Sun. If the orbital distance is shorter, then the orbital period will also be shorter, according to Kepler's third law.

- These factors makes searching the habitable zone easier with the Doppler and the transit techniques. The Doppler signal gets bigger as the period gets shorter. For transits, the probability for an orbit to be aligned properly goes inversely as the orbital distance, so for our M-dwarf planet, this probability is boosted by a factor of 4 or 5. Even better, an earthlike planet will produce a larger transit signal if it orbits an M dwarf than a sunlike star.

Searching for M Dwarfs

- All these factors—the high abundance of M dwarfs, the bigger signals, the shorter periods, and the higher transit probability—accelerate the search for Earth-sized planets in the habitable zone.

- The main drawback of M dwarfs is that they're so faint, which neutralizes, to some extent, the advantages of the bigger signals. Fainter stars deliver fewer photons to our telescopes, and that leads to higher levels of photon noise. So, the crucial quantity for detection—the signal-to-noise ratio—may or may not be improved.

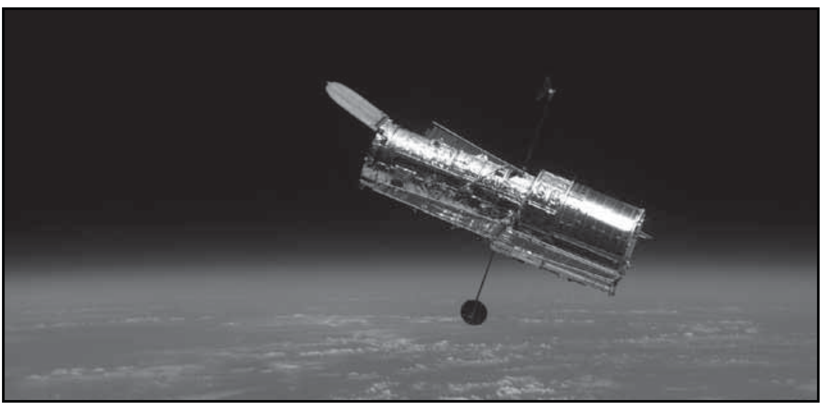
- In recent years, though, investigators have decided that on balance, the M dwarfs represent a good opportunity, and they're designing surveys that specifically target M dwarfs as a fast track to finding potentially habitable planets.

- One such survey, started by David Charbonneau at Harvard University, is called MEarth. Instead of monitoring many M dwarfs at the same time, they monitor them one at a time. They identified the brightest few thousand M dwarfs, which are spread out over the whole sky, and they're tracking the brightness of each star for long enough to check for transits of planets in the habitable zone.

- So far, they've only found one planet: GJ 1214b. It's not in the habitable zone, but it was nevertheless a blockbuster discovery. It was, and still is, the smallest planet for which we've detected the planet's atmosphere. The planet is about twice the size of Earth, putting it into that poorly understood size regime—in between the sizes of Earth and Neptune.

- The star in the GJ 1214 system is only 16% as massive as the Sun, 20% of the size of the Sun, and 1/300 as luminous as the Sun. Given the planet's orbit, at a distance of only 1/70 of an AU, and an orbital period of only 38 hours, the planet is too hot to be habitable. The planet's surface temperature is probably around 900° Fahrenheit.

- But it's still a useful system because the transit signal is so big compared to what it would have been around a sunlike star. During



GJ 1214b is the exoplanet that the Hubble Space Telescope has spent the most time staring at.

transits, the starlight goes down by 1.5%. The same planet around a sunlike star would cause a dip 25 times smaller, or 0.064%, which would be very difficult to detect. That's why it's possible to study the atmosphere of GJ 1214b with such relative ease. That also explains why GJ 1214b is the exoplanet that the Hubble Space Telescope has spent the most time staring at.

- However, what we have learned about this planet's atmosphere has been disappointing. When investigators used all the data to construct the spectrum of the planet's atmosphere, they found that it is featureless. There's no detectable absorption by sodium, water, methane, or anything else—just a gray spectrum.

- Why don't we see the usual dark lines at the particular wavelengths that are absorbed by the atoms and molecules in the atmosphere? The consensus is that this planet is very cloudy. If there are clouds in the high atmosphere, then they will block the light from the star by the same amount, regardless of wavelength or what the clouds are made of. Planetwide, pervasive clouds seem to be spoiling our attempts to use transits to study exoplanet atmospheres.

- The MEarth survey is not the only one targeting M dwarfs. In fact, the Kepler survey also looked at some M dwarfs. But the vast majority of stars Kepler monitored were G dwarfs, not M dwarfs, because the top-level mission goal was finding earthlike planets around sunlike stars.

- Out of the 150,000 stars that Kepler monitored for 4.5 years, only a few thousand were M dwarfs. That wasn't very many, but it was enough to show that planets are common around M dwarfs—at least as common as around G dwarfs. Comparing the 2 types of stars, it seems that planets around M dwarfs tend to be a bit smaller and a bit closer in than planets around G dwarfs. And, just like G dwarfs, the M dwarfs monitored by Kepler often have compact multiplanet systems.

Life on Planets around M Dwarfs

- Some scientists are concerned that even if a planet is inside the habitable zone of an M dwarf, life would be very unlikely because of some of those star's special properties.

- One problem is that M dwarfs flare up and burst with ultraviolet radiation, X-rays, and energetic particles to a much greater degree than the Sun. On the other hand, these events are only really frequent within the first billion years or so of the life of an M dwarf, so maybe the emergence of life would take longer around an M dwarf than around a G dwarf.

- There are a few other potential problems. One is that because the habitable zone occurs closer to the star, the tidal forces on the planet are going to be stronger than they are for planets in the habitable zone of sunlike stars. The tidal forces are so strong that they'll be able to synchronize the planet's rotation with its orbital.

- In the fullness of time, tidal forces tend to equalize a planet's "year" with its "day." The planet would always show the same face to the star. One side of the planet would be permanently daytime and hot, and the flipside of the planet would be in perpetual darkness and cold.

- This is potentially problematic because in climate models of tidally synchronized planets, water evaporates on the hot side, gets blown by winds over to the cold side, and then freezes—and gets stuck as solid ice on the cold side forever. So, even if the planet is officially within the habitable zone, it might be difficult to arrange for liquid water.

- Another issue is related to the relatively low temperature of an M dwarf. Whenever something is glowing because it is hot—so-called thermal radiation—then the color and the spectrum of that radiation depends on the temperature of the glowing object. Compared to a hot object, a cold object will emit less light overall, and the light will be redder. In fact, most of the radiation would be in the infrared

range of the spectrum, so the planets would be bathed in infrared radiation instead of visible light.

- And, some have argued, that's a problem. One of the key aspects of life on Earth is photosynthesis, which relies on the ability of plants, and some bacteria, to absorb photons of visible light and use the energy of those photons to drive a complicated network of chemical reactions. Those reactions are the foundation of all the life on Earth's surface.

- The infrared problem is interesting but certainly does not rule out life around M dwarfs. Nobody has been able to dream up a particular set of chemical reactions that might replace photosynthesis, but it's really difficult to imagine all the possibilities. Life does have a way of living in the strangest places on Earth, including the deep ocean, far away from any light source.

Suggested Reading

Kiang, "The Color of Plants on Other Worlds."

Lemonick, *Mirror Earth*.

Ryden and Peterson, *Foundations of Astrophysics*, chap. 14.

Tarter, "A Reappraisal of the Habitability of Planets around M Dwarf Stars."

Questions to Consider

1. Historically, why did it take so long to realize that M dwarfs are more common than sunlike stars? Could there be an even more common type of star that is currently being overlooked?

2. What would be the most serious challenge to life arising on a planet around an M dwarf?

Living with a Giant Star

Lecture 17

This lecture pursues the idea of searching for planets around stars unlike the Sun—specifically, giant stars. One reason to do this is that we want to know the ultimate fate of the Earth. The Sun will one day become a giant star. Dwarf stars turn into giant stars. The life history of stars—the subject of stellar evolution—is a fascinating topic. In this lecture, you will be introduced to just the principles of stellar evolution that are crucial for the discussion of exoplanets.

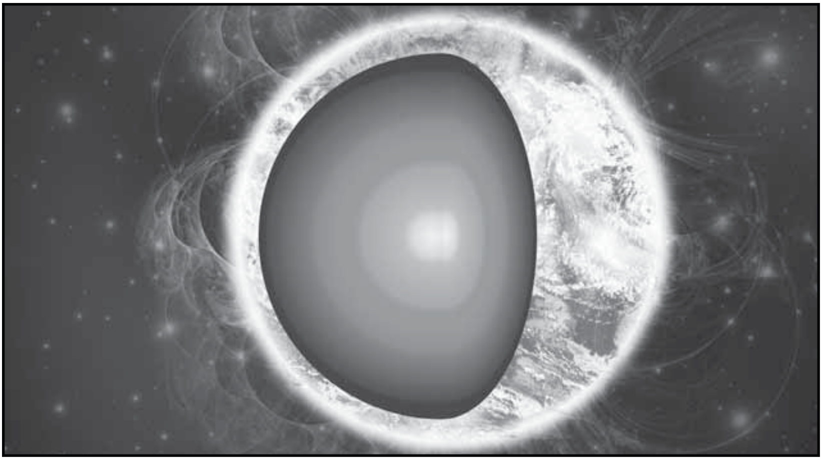
Giant Stars

- The energy that makes stars shine comes from nuclear fusion. At the center of the Sun, conditions are so hot and dense that hydrogen nuclei are forced together to fuse into helium nuclei—a nuclear reaction that releases a lot of energy. The resulting heat and pressure prevent the Sun from collapsing under its own gravity; in other words, the nuclear reactions allow the Sun to maintain hydrostatic balance. The energy released by fusion is also what's responsible for the light that escapes from the Sun and streams into space.

- The Sun started with enough hydrogen in its core to burn for about 9 billion years, and it's 4.5 billion years old, so it's used up about half the hydrogen in its core. What will happen when it runs out?

- Over all those billions of years, the helium "ash" from the nuclear reactions sinks down to the center of the Sun and gets compressed, forming a denser core. Eventually, there's no more hydrogen left in the core, so the core becomes inert. It's not producing heat anymore, so there's less pressure to resist gravity, causing the core to compress still further.

- Even though there's no hydrogen within the core, there's still hydrogen at higher altitudes within the star, and as the star compresses, eventually the conditions just outside the core become hot and dense



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The Sun has used up about half the hydrogen in its core: It started with enough hydrogen to burn for about 9 billion years, and it's 4.5 billion years old.

enough to ignite that hydrogen and start fusing it into helium. So, the star is still producing energy through nuclear fusion—it's just that the fusion is no longer happening at the center of the star. It's happening in a thin layer, or shell, surrounding the inert core of helium.

- This so-called shell burning is not as stable as the original situation, when the burning was happening at the center. This is because as time goes on, the core is getting evermore compressed, gradually causing it to shrink, which causes the overlying shell of burning hydrogen to get denser and hotter, accelerating the nuclear reactions in the shell. So, the reactions in the shell proceed more rapidly and recklessly than they do when they take place at the center of a star.

- The outcome of this shell-burning mode of nuclear fusion is that the internal structure of the star changes completely. The core becomes extremely dense, and the shell of fusing hydrogen pumps tons of energy into the higher, outer layers of the star. Those outer layers heat up and expand, puffing up to many times their original size, resulting in a tiny, dense core at the center of a distended, bloated balloon of hydrogen. A giant star is born. And it grows and grows.

- It’s a fascinating series of events, but what will happen to the Earth and the other planets as this happens to the Sun? Will the Earth be engulfed by the Sun and totally destroyed? We don’t know.

- Even though the Sun’s surface will only reach out to the orbit of Venus, the Earth is still vulnerable. The tidal force between the Sun and the planets causes the planets’ orbits to spiral inward, so the Earth might succumb to tidal decay and fall into the Sun.

- But it’s not a foregone conclusion, partly because the timescale for orbital tidal decay is unknown and also because there’s a different process, called mass loss, that tends to push planets outward. As the Sun grows into a giant star, its radiation gets so intense that it exerts a powerful pressure on the outer layers of material, creating a wind that carries material out into space. So, the Sun starts shedding its outer layers.

- As a star gradually loses mass, its gravitational pull on the planets weakens. This causes the planets to spiral outward into more distant orbits. Even though the consequences of mass loss can be calculated from basic physics, the details of how strong the Sun’s wind will become, as well as how much mass it will lose and when, are devilishly difficult to calculate.

- One way to make progress is to look for planets around stars that have already become giants. That’s a reason to look for planets around giant stars, even though giant stars are not very cooperative subjects for our planet-searching techniques.

- In addition to producing tiny transit signals and having very distant habitable zones that are difficult to search, giant stars are hostile to precise Doppler measurements. Their surfaces are not as stable as those of dwarf stars. Giant stars pulsate and vibrate. All those motions produce Doppler shifts that have nothing to do with planets or orbits, and all those extra, random Doppler shifts interfere with our measurements.

- There is a shameful number of planets that were "discovered" around giant stars that later turned out not to exist. Nevertheless, a few brave and persistent astronomers have found some genuine planets around giant stars.

- Planets that have been found around giant stars tend to be massive, with orbits wider than 1 AU. Around a dwarf star, there's about a 10% chance of finding a giant planet within 1 AU, but for giant stars, that probability is lower. That's a clue that the close-in giant planets—the misplaced giant planets—get destroyed when a star swells up and becomes a giant itself, presumably due to orbital tidal decay.

- There's another clue that tidal forces are important, too: The planets around giant stars tend to have more circular orbits, on average, than similar planets around dwarf stars. This makes sense because tidal forces cause orbits to gradually become more circular with time.

- So far, the biggest giant stars with known planets are about 50 times the size of the Sun. That's about 1/5 of an AU, about half the size of Mercury's orbit. And the planets are at a distance of about 2 AU.

Stellar Pulsations

- When the surface of a star develops waves on it, the speed and height of the waves depend sensitively on the conditions inside the star. By observing the pulsations on the surface, we can learn what's going on inside. This is called asteroseismology.

- We can detect the waves on a star's surface by tracking its Doppler shift, just as we do when we want to find planets. Or, we can track its brightness, just as we do when we want to find transiting planets. The same techniques we use to find planets can also teach us about the internal structure of stars. Sometimes the pulsations can mimic the signal from a planet, but often, the seismic disturbances can be separated from any planet signals, because they have different timescales.

- When you detect the pulsations, the first thing you learn is the speed of waves within the star. Because this speed depends on the star's density, you can use the data to calculate the star's density. That helps you figure out if it's a dwarf, or a giant, or something in between.

- In addition to density, the precise periods of all those pulsations depend on the average particle mass inside the star. This allows you to figure out how much hydrogen fuel the star has burned through nuclear fusion. Helium is heavier than hydrogen, so when hydrogen fuses together to make helium, the average particle mass goes up.

- That's terrific, because you get to learn how old the star is—how long it's been fusing hydrogen in its core. Measuring the ages of stars is one of the most difficult problems in stellar astrophysics, but it's essential if you want to understand how stars change over time.

- Possibly the most amazing thing asteroseismology has revealed is the internal rotation of stars. All stars rotate. The Sun spins around about once a month. We can tell that by tracking sunspots. But sunspots are on the surface of the Sun—what about the inside? There's no guarantee that the insides of stars rotate at the same rate as the outsides.

- Fortunately, the internal rotation of stars also affects the pattern of waves on the surface. This is because the waves that propagate in the same direction as the rotation will have a different speed than the waves that go against the rotation.

- Using this technique, asteroseismologists figured out that for the Sun, as you go deeper inside, the rotation doesn't change very much. But using Kepler data, they've found that in giant stars, the inside rotates much faster than the outside. The cores of some giants are rotating 10 times faster than their surfaces.

- In a few cases, you can figure out not just how fast the star is rotating, but also in which direction it's rotating. For stars with planets, this means that we can use asteroseismology to measure the

stellar obliquity—the orientation of the star relative to the planetary orbit, and a possible clue about planet formation.

Stellar Evolution

- In the story of stellar evolution, the star's core becomes an inert ball of helium that is gradually contracting under its own gravity and surrounded by a spherical shell of burning hydrogen. It's under these conditions that the outer layers of the star puff up and the star becomes a giant. The giant phase of stellar evolution is fairly brief.

- Next, the helium core gets compressed to such a high density and pressure that the helium starts to fuse. It gets smashed together to form carbon, oxygen, and other, heavier elements. This stabilizes the star for a while. It stops growing, and actually shrinks a bit, and settles down for a few hundred million years—but the helium gets used up quickly.

- Then, it's kind of a repeat of what happened when the star ran out of hydrogen. You have an inert core—except this time it's made of carbon and oxygen—that is gradually contracting and surrounding this core with a thin layer of burning helium.

- So, there's another phase of shell burning, but this time the shell is made of helium instead of hydrogen. And just as before, shell burning causes the star to puff up again and become an even bigger giant.

- For massive stars, this process just keeps going and going. Stars that are, for example, 10 times more massive than the Sun, keep burning fuel after fuel, fusing heavier and heavier elements, until they manage to forge iron within their cores. Then, the star collapses. The gravity of the star becomes unopposed, because there's no more heat and pressure to prevent all the star's mass from contracting under its own powerful gravity. Hydrostatic balance is impossible, which is why the star collapses.

- Depending on the star's total mass, it can collapse all the way down into a black hole, or it could form a neutron star, in which case

the material falling onto the newborn neutron star reflects off the surface and explodes into space—that's a supernova.

- The Sun, and all stars less massive than the Sun, have a more peaceful retirement plan. While they're burning helium in their cores, they lose so much mass due to their winds that they end up blowing away their entire exteriors.

- You end up with just a naked core, made mainly of carbon and oxygen, without the weight of all that other material pressing down on it. In that situation, the core is stable; it doesn't get compressed enough to ignite the carbon and oxygen. This exposed core is a white dwarf. It starts out as an extremely hot, dense little planet-sized cinder, and then gradually cools and fades into darkness over billions of years.

- Would it be possible for planets to survive all these events? Could there be life on a planet around a white dwarf, despite the gradual fading and senescence of its parent star? Some theorists have begun speculating on these possibilities, and some observers have started searching for planets around white dwarfs. None have yet been found.

Suggested Reading

Carroll and Ostlie, *An Introduction to Modern Astrophysics*, chap. 13.

Laughlin, "From Here to Eternity."

Stassun, *The Life and Death of Stars*.

Questions to Consider

1. How can we predict the exact fate of the Sun with great confidence, given that the events in question are billions of years in the future?

2. Could there be life on a planet surrounding a white dwarf star? If so, would it be easier or more difficult to detect than life in a normal planetary system?

Our Nearest Exoplanetary Neighbors

Lecture 18

So far, this course has focused on the "what" and "why" questions of exoplanetary science. What are the properties of individual planets and categories of planetary systems? Why are they sometimes so different from the properties of the solar system? In this lecture, you will put aside the "what" and "why" to consider the "where" aspects of exoplanetary science, to get a sense of place in this field: Where in the universe are these new exoplanetary systems?

The Milky Way Galaxy

- All the exoplanets that we have found so far are within our own galaxy. A galaxy is a collection of multitudes of stars orbiting in complex and often beautiful patterns. Our home galaxy—the Milky Way—is fairly typical, with about 100 billion stars. It's a spiral galaxy, meaning that the stars are organized into a series of spirals around a bright center.

- Spiral galaxies, or disk galaxies, are not the only type of galaxies. In the nearby universe, about 1/3 of galaxies are elliptical galaxies, which just look like big blobs of stars.

- The universe as a whole is overflowing with galaxies. Studying distant galaxies—how they're arranged, how they've changed over time, and how fast they're rushing away from each other as the universe expands—is the province of cosmology.

- The Doppler technique requires a lot of starlight, because to measure Doppler shifts, you have to spread out the light and examine the spectrum in fine detail, so the stars that have been best explored with the Doppler technique are among the brightest stars in our sky, which tend to be the nearest stars. Most of them are within a few hundred light-years—the distance that light travels in

1 Earth year, which works out to be nearly 6 trillion miles—just a tiny portion of the galaxy.

- As for the transit technique, not all exoplanets transit; in fact, only a small fraction has their orbits oriented correctly for us to see transits. Transiting planets are rare, and we have to look farther away to find them, on average.

- In fact there's another reason why the known transiting planets are farther away than the Doppler planets. It's because the Kepler telescope, which found the vast majority of transiting planets known today, deliberately searched faraway stars rather than the nearest and brightest stars. The typical Kepler planet is a few thousand light-years away, as compared to a few hundred light-years for the Doppler planets.

- Kepler did this for practical reasons. Within the limited field of view of the Kepler telescope, there simply aren't that many nearby and bright stars. So, to have enough stars to make the search worthwhile—to be able to search a few hundred thousand stars for transits—it was necessary to monitor all of the relatively faraway and faint stars in that particular direction.

- Because Kepler provided such a bounty of new knowledge, we find ourselves in the paradoxical situation of knowing more about the distant planets along a particular arbitrary line through the galaxy than we do about the planets closer to home. Nevertheless, we have gotten to know a few of the locals, even if there's still a lot more of our neighborhood waiting to be explored.

Alpha Centauri

- Alpha Centauri is the nearest star system to Earth, about 4.5 light-years away. There are 3 stars in the Alpha Centauri system. There's a sunlike star—type G—along with a smaller and cooler type K star, and they go around their center of mass on elliptical orbits, with a long dimension of about 15 AU and a period of about 80

years. Surrounding them both, at a distance of about 15,000 AU, is a faint, red M dwarf.

- Because these stars are so close to the Earth, they've been scrutinized carefully for exoplanets. The only one that's been found is around the K star. In 2012, the Geneva-based exoplanet group announced that the K star is wobbling with a period of 3.2 days, with a speed of half a meter per second—an orbital speed that would be caused by an Earth-mass planet. So, the Alpha Centauri system may be home to a hot rocky planet.

- This was a major result, but it's not universally accepted by workers in this field. The trouble is that the signal is very small and doesn't stand out from the noise as clearly as we would like it to. The Swiss investigators worked diligently to separate this candidate planetary signal from all the other sources of Doppler shifts, such as the orbit of the G and K stars around each other, but it's difficult to know if their methods worked well enough to trust completely.

- It'll be interesting to see if this signal persists as the star is monitored over a longer time. Unfortunately, it's becoming more difficult to do that, because the G star and the K star are approaching the part of their elliptical orbit when they're closest together. That causes the light from both stars to blend together in our spectrographs and makes it difficult to isolate the light from the K star and track its Doppler shift. We might have to wait 5 or 10 years for the stars to begin moving apart before we can obtain a more definitive answer about whether this rocky planet next door really exists.

Epsilon Eridani

- The next nearest star with a known exoplanet is a star called Epsilon Eridani, which is in the 11th nearest system and at a distance of 10.5 light-years from the Sun. It's a little smaller and cooler than the Sun—an orange dwarf, or a K dwarf. It's also younger than the Sun; it's about half a billion years old, as compared to the Sun's age of 5 billion years.

The star known as Epsilon Eridani is smaller, cooler, and younger than the Sun.

- The planet was found with the Doppler technique. It has a minimum mass of 90% of Jupiter's mass and an orbital distance of 3.4 AU. So, it's likely a gas giant, comparable to Jupiter but with a somewhat smaller orbit. In our solar system, it would be located in the asteroid belt between Mars and Jupiter.

- The Epsilon Eridani planet is controversial for the same reason as the rocky planet in Alpha Centauri. The Doppler data are not as good as we'd like them to be. In this case, it's because the star produces a lot of intrinsic noise. Young stars have big star spots and unstable surfaces that produce Doppler shifts that have nothing to do with planets. Nevertheless, the Doppler signal has been observed for a few complete cycles. So, it's a decent bet that the nearest known giant planet is around Epsilon Eridani.

Gliese 15 and GJ 674

- After Epsilon Eridani, the next closest known exoplanet, called Gliese 15, is a medium-sized planet—somewhere between the Earth and Neptune in mass—going around an M dwarf. It has a tiny orbit, only 7% the size of the Earth's orbit, and a period of 11 days.

- The next planet, named GJ 674, is also a super-Earth or sub-Neptune closely orbiting an M dwarf. It shouldn't be surprising that

there are many midsized planets around M dwarfs. M dwarfs are the most common type of star in the galaxy, and midsized planets are the most common type of known planet. Both Gliese 15 and GJ 674 are within 15 light-years of Earth.

55 Cancri and GJ 1214

- So far, we've addressed planets found with the Doppler technique, so we don't know their true masses or sizes, because all we get from the Doppler technique is the minimum mass. It's even questionable whether some of these claimed planets really exist. But with transiting planets, we do know the mass and size, without any ambiguity, and there's little room for doubt that the planet is there.

- The nearest transiting planet known today is around a star named 55 Cancri, which is very similar to the Sun and is 40 light-years away. This star has a big planetary system, with at least 5 planets that have been revealed over the years through the Doppler technique. Four are gas giants, with orbital distances ranging from 0.1 AU on the inside to 5.7 AU on the outside, similar to Jupiter's orbit. It's the 5th planet—known as planet "e," the 5th letter of the alphabet—that's known to be transiting.

- Transiting data has revealed 55 Cancri "e" to be a midsized planet, about twice the size of the Earth, with an orbit smaller than 1/60 of an AU. It goes around its star every 18 hours. So, this is an ultrashort-period planet, with an extremely hot dayside of several thousand degrees Celsius. The star is bright enough that it should be just visible with your naked eyes, according to the usual rule of thumb given in astronomy textbooks.

- The second closest transiting planet known today is also a midsized planet, about twice the size of the Earth, but this one is around an M dwarf, 47 light-years away. It's called GJ 1214. The planet was found by the team called MEarth, which searches for transiting planets specifically around M dwarfs.

Suggested Reading

Carroll and Ostlie, *An Introduction to Modern Astrophysics*, chap. 24.

Exoplanets.org. http://exoplanets.org.

Ryden and Peterson, *Foundations of Astrophysics*, chap. 19.

Questions to Consider

1. Currently, we're in the strange situation of knowing more about earthlike planets around distant stars than the nearest stars. On what other occasions in the history of exploration have we known more about relatively distant places than nearby places?

2. If an earthlike exoplanet were definitively detected in the Alpha Centauri system, would there likely be major changes to our national or international space programs?

Finding Planets with Gravitational Lensing

Lecture 19

In this lecture, you will be introduced to a technique for finding exoplanets that is different from the Doppler, astrometric, and transit methods. This technique, called gravitational lensing, doesn't involve tracking the host star's brightness or spectrum. In fact, we don't need to detect any light from the star, yet we can use this technique to find planets all the way across the galaxy. It doesn't depend on the physics of orbital motion; rather, it depends on the less familiar physical principles of relativity.

Einstein's Theory of General Relativity

- Anytime you have an object with mass, it will pull on any other objects with mass. That's the universal law of gravity: Masses inevitably attract one another. But what about light? Is light deflected by gravity?

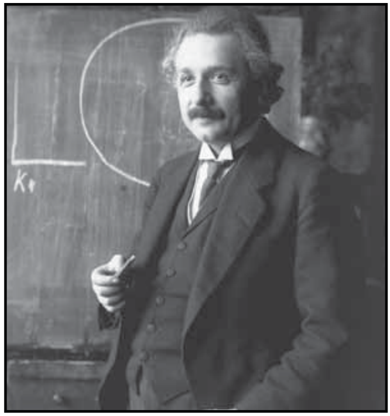
- Albert Einstein's theory is that light does get deflected by gravity, even though photons have 0 mass. In his theory, space and time are part of a single entity called space-time, and gravity is the curvature of space-time. Massive objects cause space-time to be curved, and whenever anything else is moving in space-time, it follows the curvature of space-time. That's the deflection we attribute to the force of gravity.

- How much does light get deflected? According to general relativity, the deflection is $4GM/Rc^2$, which is 1.76 arcseconds.

- When we measure the apparent positions of stars when the Sun is nearby during a total solar eclipse, the results show that the stars near the Sun get shifted according to Einstein's formula. Light is deflected by gravity, and Einstein's equations tell us exactly how much.

- In fact, Einstein's equations tell us that there's a close analogy between general relativity and the optics of glass lenses, as far as

the behavior of light is concerned. According to relativity, if all you want to do is predict light paths, then a gravitational field acts as though it changes the index of refraction of empty space.



Albert Einstein (1879–1955) proposed the theory of general relativity, in which space and time are part of a single entity called space-time and gravity is the curvature of space-time.

- The index of refraction is a number that characterizes a piece of glass. It specifies the factor by which light slows down in the glass, which is related to how much light gets deflected by the glass. In relativity, the speed of light never actually changes; what's really happening is that a gravitational field changes the length of paths in space. Gravity curves space-time.

- But if all you want to do is calculate the trajectories of photons, then mathematically it is okay to forget about curved space-time and think of a gravitational field as a strange piece of glass permeating space. The glass is denser where the gravitational field is stronger, and it's less dense where the field is weaker. So, the region around the Sun, for example, acts like a weirdly shaped piece of glass that bends the light from distant stars.

Gravitational Lensing

- Gravitational lensing is the idea that massive objects, through their gravity, deflect light as if they were glass lenses. Actually, the name "gravitational lens" might give you the wrong idea. A real lens is designed to bring all the light that hits it to sharp focus and provide a magnified but still accurate image of what's behind it. Gravitational lensing is not like that: The "image" that it forms of things in the background is stretched and distorted.

- Einstein considered what would happen if 2 different stars happened to be along nearly exactly the same line of sight, with one star in the foreground and the other star about twice as far away in the background. He realized that the gravity of the foreground star would create a specific type of mirage: The light from the background star would be split into 2 images, a fictitious double star. And each of the 2 images would be stretched and magnified.

- Einstein also realized that for this to actually happen, the stars would need to be lined up nearly exactly in the sky—within a few thousandths of an arcsecond. And the 2 images of the background star would also be separated by a few thousandths of an arcsecond. We call that typical separation between the images the Einstein radius.

- However, at this point, Einstein dropped the ball. Although he did the math correctly, he thought there was no way this phenomenon would ever be observed. The angles were just too small to be measurable, and the odds that 2 stars would line up so perfectly in the sky were too low—less than 1 in a million.

- What Einstein didn't realize was that to detect this phenomenon, you don't have to measure the tiny angles. You don't need to actually see the fictitious double star. Instead, you use the fact that the light from the background star is magnified: The mirage appears brighter than the background star normally would.

- You also use the fact that the foreground and background stars are moving, randomly, relative to each other. They're following different paths within the Milky Way, so their perfect alignment in the sky is only temporary. What you see is that the background star appears to get much brighter as the foreground star drifts in front, and then everything goes back to normal as the foreground star drifts away. The gravity from the foreground star temporarily magnifies the background star, and that allows you to recognize that something special has occurred.

- The problem of the low probability for these chance alignments can be solved by monitoring millions of stars at once for temporary brightening events, called lensing events. Even with the help of technology, it’s a lot of work to find these lensing events.

- The astronomers who ultimately succeeded, in 1993, were using gravitational lensing to look for black holes or other dark objects floating around the galaxy. In a lensing event, the only thing that matters about the foreground object is its mass. That’s what creates the gravitational field. It doesn’t matter if the foreground object happens to be lit up as a star or if it’s completely dark, like a black hole.

- Gravitational lensing is a great tool for finding massive objects in our galaxy that do not happen to emit much light. Planets don’t emit much light, and gravitational lensing provides a tool for finding them.

Planet Detection

- To use the technique of gravitational lensing, you detect planets by identifying lensing events caused by their host stars and then search very carefully for any additional short-lived brightenings. The duration of the extra blip of brightness tells you the mass of the planet, and the timing of the blip tells you something about where the planet is located around the foreground star.

- In reality, the situation is not this simple. The lensing effect of a planet need not take the form of a simple blip of extra magnification; it can produce other, more complex patterns of brightness. But the basic idea is the same: Look for any departures from a “normal” lensing event that can be attributed to planets.

- This technique has certain strengths and weaknesses relative to other planet-finding techniques. On the positive side, the lensing signals are not nearly as tiny and subtle as the Doppler and transit signals.

- On the negative side, unlike the Doppler and transit methods, the lensing events are one-time affairs: Once the stars drift apart and

are no longer perfectly aligned on the sky, the show is over, and it never repeats. The lensing technique is mainly good for collecting planet statistics—how many planets are out there and what are their average properties—rather than studying individual planets.

- Another feature of lensing is that it's most sensitive to planets with orbital distances of a few astronomical units, so lensing is sensitive to planets in relatively wide orbits, compared to the Doppler and transit techniques. That gives lensing a special role in this field: We can use it to study the outer regions of planetary systems and the outer regions of the galaxy.

- Furthermore, the lensing technique doesn't rely on detecting any light from the foreground star or planet. The lensing is caused by their masses, not their brightness. That means we can use the lensing technique to find planets around a wide range of stars, including very faint stars, such as M dwarfs, white dwarfs, brown dwarfs, and even black holes.

- On the other hand, this same feature means that often, when you find a planet using gravitational lensing, you have no idea what kind of star it's orbiting—precisely because you can't see it. So, our knowledge is more limited than it is for the Doppler and transiting planets.

Gravitational Lensing Discoveries

- The first discovery of a planet using this technique was reported in 2004 by a large group of astronomers who used telescopes in Chile and New Zealand to stare at millions of stars in the direction of the center of the Milky Way.

- This led to the discovery of hundreds of lensing events, and during one of those events, the star underwent some extra brightenings and fadings in just the manner one expects from the gravitational lensing by a planet. The planet turned out to be a giant, about 50% more massive than Jupiter, and orbiting at a distance of about 3 AU, the sweet spot of the lensing technique.

- Since then, about 20 more planets have been found with this technique. The majority are Neptune-mass planets in orbits of a few AU, and they're probably orbiting M dwarfs. In many cases, we can't actually see the host star directly, so our knowledge is limited, but given that M dwarfs are the most numerous stars in the galaxy, we expect that most of the time the lensing star is going to be an M dwarf.

- The main result of the microlensing surveys has been that M dwarfs commonly have Neptune-mass planets in wide orbits. Another, more surprising result of the microlensing surveys was the possible discovery of a population of "free-floating" planets—that is, planets that are apparently floating around by themselves in the galaxy, untethered to any star. Based on how many free-floating planets have been found, researchers gleaned from the data that there are twice as many free-floating planets in our galaxy as there are stars.

- This is a stunning result, but it is not necessarily correct. There is another interpretation of the data: The lensing signals were produced not by free-floating planets but, rather, by very wide-orbiting planets.

- Either way, it's clear that gravitational lensing is starting to deliver some interesting results about planets that couldn't have been obtained with only the more traditional Doppler and transit techniques. And microlensing is poised to make more advances in the coming years.

Suggested Reading

Einstein, "Lens-Like Action of a Star by the Deviation of Light in the Gravitational Field."

Gaudi, "Microlensing Surveys for Exoplanets."

Perryman, *The Exoplanet Handbook*, chap. 5.

Seager, ed., *Exoplanets*, chap. 5.

Questions to Consider

1. Given that gravitational microlensing events are so temporary, why are they nevertheless worth detecting and studying?

2. What types of planets are more easily found through microlensing than through the more traditional Doppler and transit techniques?

Finding Planets with Direct Imaging

Lecture 20

In this lecture, you will learn about the most obvious method for finding exoplanets: imaging. We use our telescopes to make an image of a star, and then we search that image for any evidence of planets. This sounds so simple, so direct, that the technique often goes by the name "direct imaging." But in reality, it's not at all straightforward. There are severe technological obstacles to direct imaging of exoplanets, which is why so much of this course has been about the indirect methods.

Direct Imaging

- With direct imaging, we hope to obtain a picture of a star and its surroundings that is good enough that the planets going around the star are visible as faint little points of light separate from the star. We can then hope to obtain a series of pictures, over time, showing the dots going around the star, allowing us to measure their orbits.

- We would love to have a direct view of exoplanets. If we could do this, we could measure the planets' orbits and more: We could measure their colors and the spectra and how they change with time, which would tell us about the planets' atmospheres, rotation, and maybe even their climate and variation with the seasons.

- But we don't yet have any hope of making images of the planets themselves; exoplanets are just too far away for that. They'll remain points of light for the foreseeable future. Even the stars will remain points of light, just much brighter than the planets. For the moment, our goal is to see an exoplanetary system as a series of dots surrounding a star.

- Seeing exoplanets as a bunch of little dots might seem like a limited ambition, but even that is plenty difficult. The first problem is that planets are very faint. But we know how to solve this problem: Build a big telescope to collect more light.

- Although faintness is a problem, the much more serious problem is that the star hosting the planet is much brighter. Not only do we need a big telescope, we need one that's capable of making images with very high contrast—images that can accurately represent very bright objects and very faint objects at the same time.

- Why are planets so much fainter than stars? It's because planets don't produce their own light—they just reflect starlight—and because planets are smaller than stars, they only reflect the tiniest portion of the starlight.

- If we want to directly image an exoplanet that's a twin of Earth, we need to make images with a contrast of a few billion. One sneaky way to reduce the contrast problem is to observe infrared radiation instead of visible light. The reason this helps is that planets do emit some of their own radiation, but it's mainly infrared radiation.

- A planet absorbs some of the light from the star, which causes it to warm up, and warm objects inevitably radiate away some of their energy at infrared wavelengths. When you work out the numbers, you find that the infrared contrast between the Earth and Sun is only a few million, instead of a few billion. But there's a problem: Planetary systems have other sources of infrared radiation besides planets—namely, dust.

- If we want to take advantage of the more favorable contrast of infrared observations, we need to make sure that our images have enough resolution—enough fine detail—to separate the glow of the dust from the planets.

Making Images with High Contrast and Fine Detail

- The challenge of direct imaging is making images with very high contrast and very fine detail, but there are some tricks and techniques for meeting that challenge. Why does it take fancy technology to make images with high contrast and fine detail?

- The problem is that the star is sending lots of photons to your detector, and for a variety of reasons, it's difficult to focus them all onto a tight little spot. You want all those photons to land on just one or a few pixels, but it's difficult to prevent at least some of them from spilling all over the image, including the places you want to search for planets.

- Why is it so difficult to corral all those photons into one place? First, there's the Earth's atmosphere. When photons go through air, they get deflected by an amount that depends on the temperature, density, and humidity of the air, and those things are always changing, both from place to place and in time. The result is that the image of the star dances around on the detector, which blurs the image. One way to solve this problem is to put your telescope in space—there's no atmosphere up there. But obviously it's an expensive solution, and it's not the only option.

- A second reason we can't focus the starlight as tightly as we want is that our telescope mirrors and lenses are not perfect. Any irregularities will cause some photons to scatter to where they don't belong. We have to take even more care than usual to polish and clean the mirrors, lenses, and coatings.

- Even if we do manage to keep our telescope mirror in perfect condition and even if we launch it into space, we still can't focus images arbitrarily well. That's because of a third phenomenon: diffraction. Whenever light encounters an obstacle in its path, it gets deflected, at least a little bit, around the obstacle.

- Diffraction is one of light's wavelike properties, as opposed to its particle-like, photon properties. Any kind of traveling wave—including light—undergoes diffraction. When light enters the circular opening of a telescope, the circular edge acts as an obstacle, and the light diffracts. This makes the light from a star appear to come from a range of angles in the sky, instead of just one precise location, and that causes the image of the star to smear out and look blurry.

- The fundamental problem is the blur caused by the primary optical element in the telescope, the main mirror or lens that intercepts the light. So, diffraction is less of a problem, in principle, for bigger telescopes. In practice, the atmosphere and the imperfect optics conspire to prevent us from reaching the diffraction limit.

- Fortunately, though, some astronomers and optical engineers have come up with clever ways to reverse the ruinous effects of the atmosphere and optical problems and get close to the ultimate limit imposed by diffraction.

- The basic idea is to build telescope mirrors whose shapes can be adjusted. You put lots of pistons on the backside of the mirror that can push and pull with precisely controlled forces. This trick is called active optics.

- For example, the Magellan telescopes in northern Chile have a primary mirror that is about 6.5 meters across. Underneath this huge mirror are 104 actuators, devices that push or pull on the mirror under computer control. Every 30 seconds, the computers analyze the latest image of a bright star, measure any distortions in the image, and figure out how much each actuator should push or pull on the mirror to bring it back into the desired shape.

- That helps keep the telescope in focus, even if the wind is blowing across the mirror or gravity is causing it to sag. But it doesn't help with the photon-scrambling effects of the atmosphere. The atmosphere varies too quickly, deflecting the stellar photons in different directions every hundredth or even thousandth of a second.

- So, if you want to try to compensate for the atmosphere, you need to track those image distortions, calculate how to push and pull on the mirror to fix the image, and then deliver those instructions to the actuators underneath the mirror, all within a few milliseconds. Amazingly, some astronomers have managed to pull this off.

- But they can't push and pull on the huge 6.5-meter mirror that quickly. It's too big and heavy for that. Instead, they build smaller, more deformable mirrors and insert these so-called secondary mirrors into the light path between the big primary mirror and the camera. This trick is called adaptive optics; the mirror quickly adapts to the changing conditions of the Earth's atmosphere.

- Adaptive optics has given a huge boost to the search for exoplanets through direct imaging. We no longer have to send telescopes into space. We can perform the search using the much larger telescopes we have on the ground.

HR 8799 and Beta Pictoris

- Stars named HR 8799 and Beta Pictoris are the 2 greatest successes of direct imaging so far. And they have a lot in common, including giant planets in wide orbits. In addition, both stars are relatively young.

- Direct imaging works best for wide-orbiting, giant, young planets. Wide orbits help by putting the planets as far from the star as possible, giving us the best chance to see them despite the star's glare. Giant planets reflect more starlight than smaller planets and emit more thermal radiation of their own. Young planets are hotter than older planets. The best chance to observe the infrared glow from a planet is when the planet is young.

- HR 8799 and Beta Pictoris also illustrate the types of things we can learn about planets from direct images that we can't learn from the Doppler, transit, or gravitational lensing techniques. For example, astronomers have observed the spectra of the planets, the actual spectrum of light emitted by the planet, without any of trickery involving transits or occultations.

- The planets around HR 8799 have reddish colors, which have been attributed to hot clouds of iron and silicates. For one of the planets, the spectrum also shows absorption due to water and carbon monoxide.

- For Beta Pictoris, the spectrum even allowed the planet's rotation rate to be measured—thanks to the Doppler shift. As the planet rotates, at any moment, half the planet is moving away from us, and that light from that side is redshifted, and the light from the other half, the approaching half, is blueshifted.

The existence of the planet Beta Pictoris b has been confirmed through the process of direct imaging.

- In our telescopes, all that light is mixed together to make a single dot in our images, but with a spectrum of that dot, we can see that the absorption lines have been broadened—smeared out in wavelength—due to the Doppler shifts. And if we measure that broadening, we can tell how fast the planet is spinning.

- The Beta Pictoris planet turns out to be spinning around every 8 hours. At the moment, it's the fastest-spinning planet we know of. And Beta Pictoris b remains the only exoplanet for which the rotation period has been measured.

- There are only about a dozen cases of planets that have been directly imaged around nearby stars. That's not very many, in comparison to the hundreds of Doppler planets or the thousands of transiting planets. But the information provided by the direct images is different and often complementary to the information we get from the other techniques. And these are early days for direct imaging.

Suggested Reading

Perryman, *The Exoplanet Handbook*, chap. 7.

Ryden and Peterson, *Foundations of Astrophysics*, chap. 6.

Seager, ed., *Exoplanets*, chap. 6.

Questions to Consider

1. Which would you rather achieve: discovery of a transiting earthlike planet or discovery of an earthlike planet through direct imaging?

2. What might you learn about a planet by monitoring the brightness and color of the "dot" that it makes in a direct image?

Near-Term Future Planet-Finding Projects
Lecture 21

The next few lectures will inform you of the most important current developments and future plans in exoplanetary science and the possible discoveries that might be made over the next few years, and even the next few decades. In this lecture, you will learn about near-term plans and projects—things that are well underway and for which it's pretty clear what is likely to be found. As you will learn in this lecture, astronomers are aggressively trying to improve the various planet-finding techniques, including direct imaging, Doppler, and transiting methods.

Advances in Direct Imaging

- The key technology that led to recent progress in direct imaging is adaptive optics—the use of a special mirror in your telescope, whose surface you can adjust with small computer-controlled pushes and pulls in order to cancel out the distorting effects of the Earth's atmosphere.

- Now, there's a new generation of adaptive-optics instruments that's being deployed on the world's biggest telescopes. What's different about these new instruments is that they have more actuators, so the mirror shape can be controlled more precisely; they operate faster, so they can keep up with the millisecond-to-millisecond variations of the atmosphere; and they have been built specifically for finding exoplanets, so they're optimized for looking at nearby, bright stars.

- The new exoplanet-finding instruments make use of an interesting piece of technology called a coronagraph, which is another way to deal with all the photons from the star—to prevent them from spraying all over your images, which is the main challenge in making direct images of exoplanets.

- There are many types of coronagraphs, but they all try to prevent the starlight from ever reaching your camera. We put some carefully

construed obstacles in the light path and thereby use the principles of diffraction to help overcome the usual diffraction limit. Basically, we use diffraction against itself.

- A coronagraph is not a new idea. It was invented in 1931 to study the faint outer atmosphere of the Sun—the corona—which is usually lost in the glare of the Sun itself. Coronagraphs have been used for years to try and detect exoplanets, but now they're being developed to a higher level of perfection.

- Two of the new generations of instruments that will be used to search for exoplanets are the Gemini Planet Imager and SPHERE. They're both adaptive-optics cameras with coronagraphs. Both are designed to achieve contrasts of around 10 million within about 1/10 of an arcsecond from bright stars, which is several times better than the instruments that came before, so it's likely that they'll turn up dozens of new planets. They'll probably be young gas giants in wide orbits.

- The Gemini Planet Imager and SPHERE can do more than just make images of the dots; they can also measure their spectra and give us a peek into the atmospheres of the planets. So, we stand to learn a lot about the temperature and the chemical makeup of newborn giant planets. They've already obtained stunning images and some spectra of planets Beta Pictoris and HR 8799.

Advances in the Doppler Technique

- The Doppler velocity you need to be able to detect if you want to find an Earth twin around a sunlike star is 9 centimeters per second. Currently, the state of the art in Doppler precision is around 50 to 100 centimeters per second, so it needs to be improved by a factor of 10 to find earthlike planets.

- One of the issues limiting our current precision is the stability of the instrument. The whole game is to observe the star's spectral absorption lines—the dark lines in its rainbow of colors—and sense tiny shifts in wavelength over time. So, we need a stable "ruler" to measure those wavelengths.

- Typically, that ruler is a series of spectral lines produced by some other element that we insert in the telescope, whether it's the dark lines of iodine or the bright lines of a glowing lamp containing thorium and argon gas. The problem is that those rulers aren't perfectly stable.

- There are many laboratory experiments going on to build more stable rulers for measuring Doppler shifts. One of the most promising uses a machine called a laser comb, which coaxes a laser to ultrashort pulses of light at extremely regular intervals—for example, every billionth of a second.

- As it turns out, the spectrum of a pulsed light source doesn't look anything like a rainbow; it looks like a ruler, a series of bright lines at regular intervals, like the teeth of a comb. So, you can send the light from a laser comb through your telescope along with light from some distant star. That way, on top of the spectrum you observe from the star, you have all those laser lines telling you the wavelength scale.

- In the lab, at least, the ruler provided by laser combs is stable enough to measure velocities of a few millimeters per second. But there have been only been a few experiments involving laser combs strapped onto actual telescopes, and the results have not been nearly as impressive. Over time, though, the laser comb is expected to become a standard piece of equipment.

- One reason why the laser comb can't fulfill all of our Doppler dreams is that there's another source of noise in our measurements, besides any instabilities in the wavelength scale: the stars themselves. The surfaces of stars are not calm and motionless; they're roiling, boiling cauldrons of plasma. All this tumult—called stellar activity—produces extra Doppler shifts ranging from a few to a few dozen meters per second, much bigger than the signal of an earthlike planet.

- It sounds hopeless, but it's not really. One saving grace is that the genuine Doppler shifts produced by planets will repeat with every orbit, but stellar activity is more random. So, we can just keep observing and see if the signal repeats.

- This isn't a perfect solution, because stars also rotate, which causes the stellar activity to appear to have a repeating pattern, too, so you have to be careful that your "planet" isn't just a stellar storm that's getting carried around the star by rotation.

- Many astronomers are working on ways of identifying and rejecting the signals from stellar activity. One possibility is to use spectrographs that can record a wider range of wavelengths. The idea is that orbital Doppler shifts should be the same no matter what kind of light is used to measure them. But that's not true for stellar activity. So, if you see that the size of your signal is smaller at infrared wavelengths than at visible wavelengths, for example, it must be due to stellar activity rather than a planet.

- Another good reason to extend the observations into the infrared regime is that's where M dwarfs emit most of their radiation. M dwarfs offer a possible shortcut to finding potentially habitable planets: Their habitable zones occur relatively close to the star, making the planets occupying the habitable zone easier to detect. That's why there are half a dozen major efforts underway to build planet-finding Doppler spectrographs that operate at infrared wavelengths.

Advances in Transit Surveys

- Anyone working on transits is now working in the shadow of NASA's amazingly successful Kepler mission, which propelled progress in this field for 4 years. Because Kepler tends to look at faraway, relatively faint stars, it has created a counterintuitive situation: We know more about transiting planets around distant stars than we do about those around the stars next door. But the next generation of transit surveys are all concentrating on the nearest, brightest stars.

- Some are upgrading small telescopes on the ground. However, the Earth's atmosphere will probably prevent them from finding planets as small as Earth. Adaptive optics isn't much help here; that allows us to make sharp images, but it doesn't improve the precision with which you can measure stellar brightness.

- Nobody has yet come up with any trick to cancel the atmospheric effects on brightness. And, of course, nobody has yet come up with any technology to annihilate clouds or stop the Sun from rising and interrupting our dark nights.

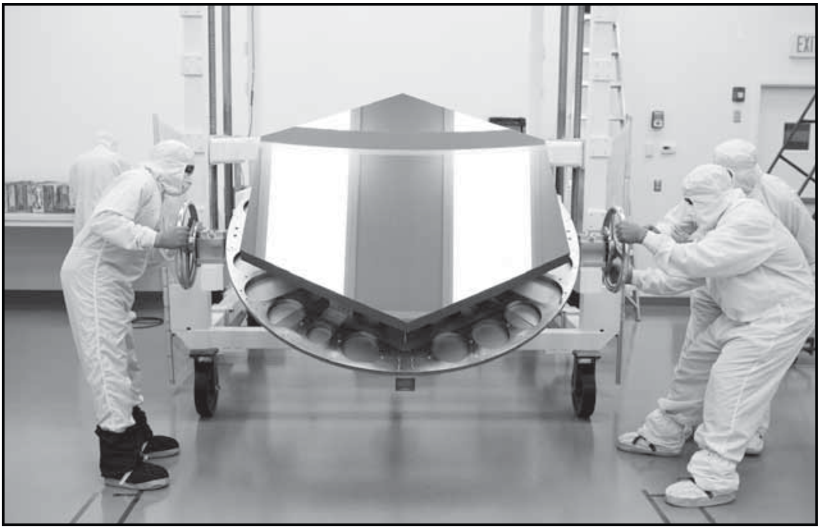
- So, what we want are space telescopes that can scan the brightest stars over the whole sky. That's the goal of NASA's next exoplanet space mission, called TESS, which stands for Transiting Exoplanet Survey Satellite. It is scheduled for launch in 2017.

- TESS is a smaller and less expensive spacecraft than Kepler. Instead of a telescope with a diameter of 1 meter, TESS uses 4 telescopes, each of which has a diameter of only 1/10 of a meter. The advantage of small telescopes is that they have wider fields of view. We need wide fields because the brightest stars are spread all over the sky; they're not all clustered in any particular direction.

- All 4 of TESS's telescopes will be pointed in different directions. Between the 4 of them, they'll keep a big stripe of the sky under surveillance, covering about 1/20 of the entire sky at a time. After about 2 years, it will cover the whole sky.

- In addition to pressures of a relatively low budget, this survey will be performed in a hurry. We want to cover the whole sky as quickly as we can, even at the expense of missing out on some of the longer-period transiting planets.

- Another space telescope is scheduled for launch in the next few years: the James Webb Space Telescope, the successor to the Hubble Space Telescope. It will be the premier observatory for studying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The successor to the Hubble Space Telescope, the James Webb Space Telescope will be the premier observatory for studying exoplanet atmospheres.

exoplanet atmospheres, thanks to its large size and its location in an incredibly stable and dark location far from the Earth.

- We eagerly look forward to using the Webb telescope to probe the atmospheres of transiting earthlike planets, to understand their compositions and climates, and even to look for any evidence of living creatures. So, it's a bit worrying that at the moment, at least, we don't know where exactly we would point the Webb telescope—we haven't yet discovered the best and brightest stars with transiting planets.

- What's worse is that the Webb telescope will have a relatively short lease on life. The mission has a built-in expiration date between 5 and 10 years after launch. After that, it will run out of the fuel it needs to maintain its orbit, and it'll be too far away from Earth to send a care package. Once it's out of fuel, the mission is over.

- The Europeans are planning a transit mission called PLATO (Planetary Transits and Oscillations of Stars) that is scheduled for launch in 2024. They're going to take their time, giving up on finding early targets for the Webb telescope in order to build a more capable observatory. TESS has four telescopes. PLATO will have about 32. TESS stares at most stars for about a month; PLATO will go for several years. And for many of those stars, PLATO will be sensitive enough to detect the subtle vibrations of their stellar surfaces, so we'll have a much better understanding of the stars we're looking at as well as the planets going around.

Suggested Reading

Perryman, *The Exoplanet Handbook*, chap. 7.

Ricker, et al, "Transiting Exoplanet Survey Satellite."

Ryden and Peterson, *Foundations of Astrophysics*, chap. 6.

Seager, ed., *Exoplanets*, chap. 6.

Questions to Consider

1. Why did the TESS mission, which looks at nearby stars, come after the Kepler mission, which looked at faraway stars?

2. How might we tell someday whether the "dot" seen in images of Fomalhaut is a real planet or something else?

Long-Term Future Planet-Finding Projects

Lecture 22

In this lecture, you will continue exploring future projects and space missions to discover new exoplanets. The previous lecture was mostly about the near term: the next 5 or 10 years. This lecture looks ahead a bit further, to the next few decades. That's enough time to plan really big and ambitious projects. But it's also far enough in the future that the details are still lacking—some of these projects haven't even settled on their names—so it's impossible to know which of these dreams will actually come true.

Future Space Missions

- The American astronomy community tries to be well organized when it comes to planning future missions. Every 10 years, they convene many meetings under the auspices of the National Academy of Sciences with the goal of reaching a consensus on astronomy's top priorities for the coming decade. It's called the Decadal Survey. The hope is to have better luck getting funding from Congress, the National Science Foundation, and NASA by presenting the government a single plan with broad support.

- The process seems to work. Usually, the top-priority project in the Decadal Survey ends up getting built—although sometimes it takes longer than a decade. An example is the Spitzer Space Telescope, the top priority of the 1991 Decadal Survey, which was launched in 2003.

- The most recent Decadal Survey was in 2010. The highest priority was a new space telescope that's tentatively being called WFIRST, an acronym that stands for Wide-Field Infrared Survey Telescope.

- What sets it apart from previous space telescopes is that it'll observe at infrared wavelengths rather than visible wavelengths, and its cameras will have a very wide field of view. It will be able to make images of a portion of the sky nearly 200 times larger than that of

the Hubble Space Telescope or its successor, the James Webb Space Telescope.

- Why are these characteristics—infrared and wide field—so important? WFIRST was conceived as a cosmology mission. Cosmology is the study of the entire universe, as opposed to any particular planet, star, or galaxy. Cosmologists want to know the mass and geometry of the entire universe and the way it has expanded and cooled since the big bang.

- Infrared observations are important for cosmology because when you observe very distant galaxies, billions of light-years away, the light emitted by those galaxies gets converted into infrared radiation by the time it reaches us. Wide-field observations are important to be able to measure the properties of millions of galaxies at once and to discover rare but important objects like distant supernovae.

- A wide-field infrared telescope is the perfect tool for a gravitational lensing survey for exoplanets. In the gravitational lensing technique, we need a wide-field telescope to monitor millions of stars for months, looking for those rare events when one star drifts across the line of sight to a more distant star and its gravity—and sometimes the gravity of its planets—temporarily magnifies the light from the background star.

- An infrared telescope gives a much better view of the center of the Milky Way, which is the best place to point your telescope if you want to monitor zillions of stars all at once.

- The plan for WFIRST is to split the observing time between cosmology and exoplanets. During the exoplanet portion, it'll spend a year staring at the center of the Milky Way, keeping tabs on 200 million luminous, faraway giant stars, waiting for them to brighten due to the gravitational lensing effect of any fainter stars and their planets in the foreground.

- The purpose is to perform a census of planets that are in relatively wide, distant orbits around their stars—the complement of the Kepler mission, which was all about planets in relatively close and short-period orbits. WFIRST also will be able to check on the claimed discovery of free-floating planets, roaming the galaxy independently of any star.

- In January of 2011, the U.S. National Reconnaissance Office (NRO), the agency responsible for spy satellites, revealed that it had 2 space telescopes that it didn't want anymore. They asked NASA if they'd have any use for them.

- Even though the spy telescopes were built for pointing at the Earth, they'd also be great for pointing at the stars. In fact, the NRO telescope mirrors are 2.4 meters across, about twice as large as the telescope that had been planned for WFIRST. So, now the plan is to use one of those obsolete spy telescopes to make cutting-edge discoveries in cosmology and exoplanetary science.

- The mission has been rebranded WFIRST-AFTA, where "AFTA" stands for Astrophysics Focused Telescope Assets, referring to the spy telescopes. If all goes according to plan, it'll be ready to launch in the mid-2020s. We're only going to use one of the new telescopes; we don't have a plan yet for the other one.

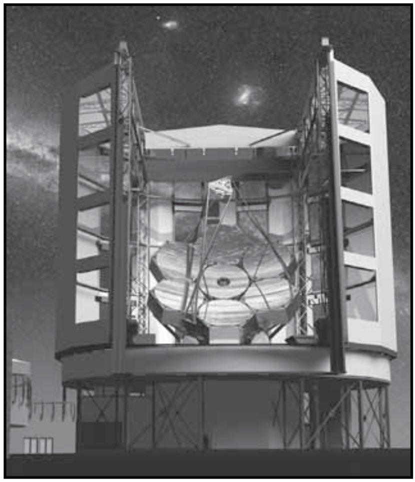
- The NRO telescopes have outstanding image sharpness, which means they're also well suited for a coronagraph, a device for direct imaging that helps you filter out the light from a bright star and make it easier to search for any orbiting planets. The current plan for WFIRST-AFTA also calls for a coronagraph on board and to spend some of the time using it to make images of 200 nearby stars.

- The images will have a contrast of about 1 billion to 1, within 1/10 of an arcsecond of the star. That's good enough to find planets just like Jupiter and Saturn, and maybe even some smaller planets similar to Uranus and Neptune.

- For the first time, we'll have the capability to make direct images of exoplanets that are exactly analogous to the giant planets in our solar system. All the existing direct images of planetary systems involve planets that are much younger, bigger, and hotter and have unusually wide orbits.

Future Developments on Earth

- As opposed to space missions, all the talk on Earth is about the next generation of large optical telescopes, which would be able to collect about 10 times as much light as today's biggest telescopes. But there's no consensus about what to build and where. At this point, the world's astronomers have divided up into 3 teams, each of which is trying to raise a billion dollars, or more, to build their telescope in the next 10 or 15 years.



The Giant Magellan Telescope will be able to measure Doppler shifts with a precision of a few centimeters per second, which is good enough to detect an Earth twin.

1. A big group of mainly American research institutes and universities is building the Giant Magellan Telescope at an observatory in northern Chile.

2. A competing group of American universities has teamed up with the governments of India, China, and Japan, among others, to build the Thirty Meter Telescope on the summit of Mauna Kea in Hawaii.

3. A large collection of European nations is banding together to build a telescope called the Extremely Large Telescope.

- None of these 3 telescopes is being built specifically to study exoplanets, but they'll all be powerful tools for that purpose. They'll have adaptive optics to help with direct imaging and spectrographs that can be used to probe the atmospheres of transiting planets.

- The Giant Magellan Telescope will have among its instruments a spectrograph that is being designed specifically for exoplanets. It'll be ultrastable and equipped with a laser comb to try and measure Doppler shifts with a precision of a few centimeters per second. That's good enough to detect an Earth twin—if we can somehow overcome the problem of the Doppler noise produced by the star itself.

Peering Further into the Future

- It seems clear that eventually we're going to want to build a telescope capable of direct imaging of earthlike planets. If we succeed in detecting very earthlike planets through the indirect methods—Doppler, transit, astrometry, or gravitational lensing—that will be cause for celebration, but it will only increase the hunger to see such a planet in a direct image.

- In addition to the simple desire to see a planet in an image, instead of a wiggle or a dip on a chart, we have scientific reasons. We can track the variations in brightness and color of the dot of an earthlike planet as a probe of the planetwide weather patterns. And the spectrum of the dot is the most straightforward way to learn about the planet's rotation, as well as the contents of its atmosphere, which might be our best shot at figuring out if there's life on the planet's surface.

- Achieving this goal is probably going to require a big space telescope, something even more capable than the James Webb Space Telescope or WFIRST-AFTA—something that can collect enough light to detect the dot of an earthlike planet while achieving a contrast of about 10 billion to 1 within a fraction of an arcsecond of its host star.

- This is so daunting that we can't even say what such a telescope would look like. In fact, even though we don't know what to build,

the project acquired a name that stuck for more than a decade: the Terrestrial Planet Finder. More recently, it's been rebranded as the New Worlds Mission or the High-Definition Space Telescope.

- Three different concepts are being pursued for this future mission. There's a vigorous, fractious, and politicized competition underway among the proponents to demonstrate their favorite technology in a laboratory setting and argue that it's what NASA should be funding in the years to come.
    1. The first concept is a coronagraph. We'd build a large space telescope with exquisitely polished mirrors and a super coronagraph. Astronomers and optical engineers are exploring exotic new coronagraph designs to try and achieve higher contrast.

    2. The second concept is to build something called a nulling interferometer. An interferometer is 2 or more different telescopes that work together to produce a single image. They do it in a very special way, relying on the wavelike properties of light, specifically on the concept of wave interference.

    3. The third concept for a future direct-imaging mission is called a starshade. The idea is to prevent the stellar photons from ever raining down into your telescope by building a giant opaque "umbrella" and flying it in front of your telescope. The umbrella, or starshade, is located in just the right location and has just the right shape to shadow the light from whichever star you want to observe. So, the starlight never reaches your telescope. It's like a coronagraph that you put outside your telescope instead of inside.

- All 3 of these options for making direct images of earthlike planets have amazing challenges, so we will have to be patient, and persistent, before we can enjoy contemplating other worlds.

Questions to Consider

1. Why are there no plans for a space mission that would search for exoplanets using the Doppler method?

2. Of the 3 possible designs for space missions for direct imaging of earthlike planets—the coronagraph, interferometer, or starshade—which sounds the most promising, and why?

The Search for Life on Exoplanets

Lecture 23

What is the progress we've made in the quest for life, and how might it play out in the years to come? As of now, we have no evidence for life anywhere else in the universe besides Earth. Space missions to the planets in the solar system have ruled out any obvious, widespread forms of life on their surfaces. The search for life inside the solar system is continuing, but in less obvious and more remote places. This lecture will focus on searching for life on exoplanets.

The Search for Life on Exoplanets

- The modern search for life on exoplanets got started in the late 1950s, long before exoplanets were discovered. Nevertheless, there was a widespread presumption that exoplanets existed, and a few scientists realized that our own communication technology had advanced to the point that we could imagine broadcasting messages to the nearest stars.

- The signals would take years to arrive, even traveling at the speed of light, but they would arrive with enough power to conceivably be detected. Therefore, if there were alien civilizations in those other star systems, they might be broadcasting to us.

- The first scientific paper on this subject was in 1959 by Giuseppe Cocconi and Philip Morrison, who made 5 points.
    1. If there are extraterrestrial civilizations, it's likely that their communications technology is ahead of ours by millions or billions of years. Our own technology is only a few hundred years old. Planets and stars persist for billions of years, so in general, other civilizations are going to be much older than ours.

    2. Sending messages is technologically more challenging than listening for messages, so it makes more sense for us to listen than to broadcast. The burden of transmitting should fall on

the older, more advanced civilizations. The challenge then becomes trying to anticipate what we should listen for.

3. We should listen for some kind of electromagnetic waves—that is, photons. Photons are the best particle for long-distance communication because they're easy to create and detect, and they travel at the fastest-possible speed, the speed of light. And they have no electric charge. Charged particles are problematic because they don't go in straight lines, and you can't control where they go.

4. Of all the types of electromagnetic waves we could use for interstellar communication, the best are radio waves, as opposed to visible light or X-rays, for example. This is because the technology for sending and receiving radio waves is more straightforward and because there's relatively little interference from natural sources of radiation. The galaxy is quiet at radio wavelengths. But even after we restrict our attention to radio waves, there are still many possibilities. Radio waves can have wavelengths anywhere in size from millimeters to kilometers, so which ones should we be monitoring?

5. There is a special radio wavelength dictated by the laws of physics: 21 centimeters. Or, expressed as a frequency of oscillation rather than a wavelength, it's 1420 megahertz on the radio dial. That's the frequency at which hydrogen, the most common element in the universe, naturally broadcasts, so it seems like the natural choice for a "hailing frequency" for any advanced civilizations.

- With these 5 points, Cocconi and Morrison laid out the strategy for the search for extraterrestrial intelligence (SETI) that has been followed to this day: We should listen, with radio telescopes, tuned near 1420 MHz.

The Drake Equation

- The first astronomer to put this SETI strategy into practice was Frank Drake. In 1960, he pointed a radio telescope at 2 of the nearest sunlike stars, Tau Ceti and Epsilon Eridani, searching for signals from any extraterrestrial civilizations.

- Drake is famous for this pioneering effort and also for his equation—the Drake equation—that tries to create a quantitative framework for SETI. His framework is kind of like trying to estimate the population of a country based on its birth rate and the average lifespan.

- Drake assumed that all over the galaxy, alien civilizations are born, thrive for some time, and then die. Then, he identified a series of terms you need to multiply together to estimate how many interstellar civilizations are actually out there at any particular moment in time, waiting for us to find them.
    1. The first term is the rate at which stars are born in our galaxy, specifically—stars that are suitable hosts for life-bearing planets.

The assumption for the Drake equation is that all over the galaxy, alien civilizations are born, thrive for some time, and then die.

2. The second term is the fraction of those stars that have planets.

3. The third term is the average number of habitable planets for those stars that have planets.

4. The fourth term is the fraction of habitable planets that are actually inhabited; this is the term representing the probability for life to emerge on a suitable planet.

5. The fifth term is the probability that life, once started, will evolve to have a high intelligence.

6. The sixth term is the probability that intelligent life will develop advanced communication technology and use it to broadcast messages.

7. Finally, to get the number of such interstellar signals that actually exist at any particular moment, we need to multiply by the last and most unsettling term in Drake's equation: the average lifetime of a civilization, once it has developed the technology for interstellar communication. Ours has lasted less than 100 years so far. How much longer can we expect to survive?

- The Drake equation poses more questions than answers. But it does give us a way to organize our thoughts about SETI and to explain what progress we have made. We now have a decent grip on 3 out of the 7 terms, based on progress over the last few decades.

- To estimate the first term, the star formation rate, you take a census of all the clusters of newborn stars in the Milky Way, and based on how many there are and their ages, you can build a model for how often stars are born.

- As for the second term, the fraction of stars with planets, we've made enormous progress over the last decade, with the help of Doppler surveys, transit surveys, and gravitational lensing surveys.

- The third term, the average number of habitable planets per star, has been the subject of intense research over just the last few years. Thanks to progress on the Doppler and transit techniques, we've finally reached the point of being able to detect small planets in the habitable zone.

- But as for the fourth through seventh terms, the ones that pertain to biology and history and sociology, we simply don't have enough information to know how likely it is that life gets started on a planet. Even if we could answer that question, we don't know how likely it is for life to attain high intelligence or high technology—or how long it persists.

- When Frank Drake and others got started in the 1960s, all they knew was the first term, the star formation rate. They had no data to inform their guesses for the second and third terms, about exoplanets. So, they simply started monitoring all the nearest sunlike stars.

- Now, we know that planets are commonplace, and we can pinpoint the nearest stars that definitely have planets, such as Pollux and 55 Cancri, and those that probably have planets, such as Epsilon Eridani and Alpha Centauri.

- Thanks to Kepler, we even know of a few distant stars that not only have planets, but have potentially habitable planets. A few SETI programs have focused intensively on those specific stars. But because our exoplanet searches are still so incomplete, most SETI programs still monitor nearby stars, regardless of what we do or don't know about the exoplanets around them.

- They use giant radio telescopes tuned to the vicinity of 1420 MHz. Another popular choice is 1700 MHz, the broadcasting frequency of the hydroxyl molecule (HO), an ion that appears whenever you have a lot of water (H_2O).

Optical SETI

- Most ongoing SETI programs are following the advice laid out by Cocconi and Morrison. But there are a few taking a different approach, looking for signals in visible light rather than radio waves: an approach called optical SETI.

- The reason to choose visible photons instead of radio waves is partly because you can focus light into a narrower beam than you can with radio waves. This is related to the fact that the wavelength of visible light is millions of times smaller than the wavelength of typical radio waves. So, if you want to send a message to a particular star in a particular direction, as opposed to broadcasting everywhere, it might be best to use light beams.

- There's another reason why light might be advantageous. Although the galaxy is quiet in radio waves, there are free electrons in interstellar space, and those roaming electrons interfere with radio signals. As a signal propagates for hundreds of light-years, the electrons broaden the range of frequencies, a phenomenon called dispersion. This garbles the signal and makes it more difficult to detect. Light doesn't suffer from dispersion; although light does have the problem that it gets blocked by dust, which radio waves sail right through.

- Visible light would seem to have another even more serious problem: How can you build a light source that competes with the enormous light output of the star at the center of your planetary system? With radio waves, the trick is to broadcast in a narrow frequency band. You can do the same with light: Use a laser, which concentrates all of its energy into an extremely specific color.

- You can do even better by concentrating the laser energy further, into very short pulses—bursts of laser radiation, on and off, lasting only a nanosecond. During those particular nanoseconds, and at those particular wavelengths, the laser pulses can outshine an entire star.

- The practitioners of optical SETI build specialized cameras that can detect extremely short pulses of laser radiation. They've hooked them up to optical telescopes and stared at some of the closest sunlike stars, including some of the stars that we now know likely have planets, such as Epsilon Eridani and Alpha Centauri. Like their colleagues in radio SETI, they haven't yet found any purposeful signals.

The Future of SETI

- Do all of these failures to find signals mean that we're all alone? Can we rule out the possibility that we have neighbors among the stars? Not really. There are so many stars to search and so many frequencies to try, and the signals themselves might be intermittent or difficult to recognize. SETI programs, even after more than 60 years, have probably barely scratched the surface.

- Another thing to realize is that they're all running on a shoestring, with minimal budgets compared to other science projects. Because their research seems to be related to UFOs and other flaky topics, they've suffered from interference by the U.S. Congress, including the revocation of NASA funding for SETI by the Senate in 1993.

- Most of the work on SETI since then has been funded privately by The Planetary Society, a grassroots organization started by Carl Sagan, Bruce Murray, Louis Freedman, and Silicon Valley philanthropists.

- Paul Allen, in particular, donated more than $30 million to fund the construction of a new and innovative radio telescope that's specifically geared toward SETI. The Allen Telescope Array is uses 42 individual radio dishes that work together as a radio interferometer. It's similar to other radio telescopes that are used in conventional astronomy, but with a wider field of view and greater scope for expansion and computational power. The telescope has been working since about 2007, but observing has been interrupted for long stretches because of financial troubles.

Suggested Reading

Billings, *Five Billion Years of Solitude*.

Cocconi and Morrison, "Searching for Interstellar Communications."

Shostak, *Confessions of an Alien Hunter*.

Wilson, "The Search for Extraterrestrial Intelligence."

Questions to Consider

1. What would you estimate for each of the factors in the Drake equation?

2. What is the appropriate level of national investment in the search for extraterrestrial intelligence?

Coming Soon: Biosignatures, Moons, and More!

Lecture 24

Although we'd love to find civilized extraterrestrials, it would still be an earth-shattering discovery if we could find anything alive, even if it's "just" some life-form similar to plants, or algae, or single-celled microbes. It would still give us a second example of a genesis, an entirely different tree of life. The search for unintelligent life—the subject of this lecture—lends itself to a more systematic approach than SETI. It's at least a little clearer what we should look for and what types of new telescopes we need to build.

The Atmospheres of Exoplanets

- Life on the surface of a planet might make itself known by changing the atmosphere in some detectable way. For example, on Earth, our air is about 78% nitrogen, 21% oxygen, and only about 1% of other gases, including argon, carbon dioxide, and water. The only reason there's so much oxygen is because of plants, which use the energy of sunlight to take the carbon out of the carbon dioxide and use it to make sugar. In the process, they spit out oxygen—that's what remains when you pluck carbon out of carbon dioxide.

- Oxygen is very chemically reactive. It's unstable. It combines with metals to make oxides, which is what rusting is. More generally, it combines with minerals on Earth's surface to incorporate itself into rocks. It also combines with nitrogen and water to form nitrates. Without plants, that oxygen would eventually disappear from the atmosphere. All the animals and other living creatures would use it up and die, and then over tens of thousands of years, any remaining oxygen would get locked up in the Earth's solid crust and oceans.

- If aliens were using their telescopes to study Earth's atmosphere from afar, they might wonder why there's so much oxygen there. They might realize that there has to be something constantly pumping oxygen into the air, and they might conclude that the most

plausible explanation for that constant pumping is the metabolism of living creatures: plants.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Plants on Earth, through the process of photosynthesis, use energy from the Sun to grow.

- Chlorophyll is the molecule that plays a starring role in photosynthesis—the process by which plants use sunlight to make sugar—and it's the molecule that's mainly responsible for the green color of plants.

- Just because you see something green on a planet doesn't mean that there must be plants. Other substances could be green, too. What's more interesting about the appearance of plants is their infrared color. If you could see infrared radiation instead of normal light, you'd see that plants are shiny. They're good emitters of infrared radiation.

- The sudden rise in brightness as you go from the red end of the spectrum into the infrared—the so-called red edge—is only seen on those parts of the Earth covered with plants and doesn't match the spectrum of any common mineral on Earth's surface or the surface of any of the other planets in the solar system. That's what makes the red edge potentially diagnostic of plants, or some other kind of starlight-harvesting creature that would presumably face the same challenge of avoiding overheating that plants do on Earth.

- Thermodynamic disequilibrium means that there's some chemical present at a level that's way out of line with what we expect, given what we know about the processes that create and destroy that chemical. When you see disequilibrium for some molecule, you know you're either looking at a temporary fluctuation that's eventually going to go back to normal, or there must be some source of energy coming from outside or some process you didn't know about that's keeping that molecule at the observed level.

- Oxygen in the Earth's atmosphere would appear to be in disequilibrium if you considered only inorganic processes like rusting and nitrate formation and didn't know about plants. Methane (CH_4) is another gas that's in disequilibrium in the Earth's atmosphere. It's a gas that you get when organic matter decays. If there were no creatures on Earth, then after a few years, all the methane would react with oxygen to form carbon dioxide and water. So, the fact that we see both oxygen and methane in the atmosphere at the same time is an even stronger disequilibrium than just seeing oxygen alone.

The Search for Biosignatures

- All these aspects of the Earth's atmosphere caused by life—oxygen, methane, and the red edge of plants—have been called biosignatures. One way to find life on exoplanets is to search for biosignatures: some gas, or combination of gases, at levels that are difficult to explain by any natural processes except for creatures that are making a living on the surface of the planet.

- What's needed, then, are better techniques for interrogating the atmospheres of exoplanets, particularly exoplanets within the habitable zones of their stars. There are 2 basic approaches for doing this.

- One is direct imaging: You build a telescope, probably a space telescope, that uses one of a few engineering principles—a coronagraph, an interferometer, or a starshade—to cope with the glare of the bright star and identify those tiny dots circling around it. Then, you send the light from one of those dots through a

spectrograph, which will tell you how bright the planet is at each of hundreds or thousands of different wavelengths. You might see a red edge, or you might see that there are certain wavelengths missing because there's a lot of oxygen and methane in the atmosphere—or other gases that are in "extreme disequilibrium."

- The other approach is to find transiting planets in the habitable zone—planets that move right in front of the star they orbit. When you've found one, you can study its atmosphere without any kind of fancy direct imaging technology. You measure the spectrum of the star when there's no planet in front and compare it to the spectrum of the star when the planet is in front and the planet's atmosphere is absorbing a small portion of the starlight. If your telescope is big enough and your spectrograph is precise enough, you'll be able to notice the extra absorption caused by the atoms and molecules in the planet's atmosphere.

- The transit technique works particularly well for stars that are M dwarfs—small, low-luminosity stars. The small size of the stars causes the transit signals to be bigger, and the low luminosity of those stars causes their habitable zones to occur at shorter orbital periods, making it easier to collect lots of data.

- The basic strategy in the search for biosignatures has 2 parts. In the near term, we'll find and study planets around M dwarfs, because that doesn't require a billion-dollar space mission. In the longer term, once those billion-dollar telescopes are launched, we'll be able to scrutinize planets that orbit stars that more closely resemble the Sun.

- Neither of these approaches is going to be easy. Not only are the signals small, but the interpretation of those signals could be murky. Suppose that we do find oxygen and methane on some distant planet. Are we going to be sure that there's no other possible explanation? Could there be some peculiar type of volcano or other exotic natural process that could be fooling us?

- The data from exoplanets might take a long time to interpret. And it's uncertain whether we'll ever be able to find a single really convincing biosignature. But maybe we'll find 3 or 4 different signatures, enough to make a really good case for life. Some of the most creative scientists are trying to think ahead about this problem.

- How long do we have to wait before we'll actually discover life on another planet? It's a good question. Based on current trends, we can anticipate how long it will take for our technology to enable the search for biosignatures. It might take 10 or 20 years to be able to search earthlike planets around M dwarfs using transits and maybe 30 to 40 years for direct imaging followed by spectroscopy of earthlike planets around sunlike stars.

- But that's not enough for a complete answer. There are just too many unknowns about how prevalent life is in the universe and how detectable it's going to be: Will they be sending interstellar signals, or will they be changing their planet's atmosphere in some unique way?

The Future of Exoplanetary Discovery

- Exoplanetary science is rapidly progressing. Based on extrapolation from our current capabilities, there are several discoveries that are likely achievable and will be important in the coming years.
    1. Moons: We do not yet know of any moons of exoplanets. They might one day be detected through their transits or by perturbing the orbit of a transiting planet. Searches to date have only been able to rule out very large moons in a relatively small sample of planets.

    2. Rings: All of the giant planets in the solar system have rings, and Saturn's rings are extremely prominent. We might see evidence for rings if we can find a planet like Saturn that has its spin axis tilted with respect to its orbit, so that the rings precess around like a top and produce a time-varying transit signal.

3. Tidal decay: We have indirect evidence that planets are occasionally swallowed by their stars after spiraling inward due to tidal forces. It would be wonderful to find direct evidence for this process by monitoring a close-in planet for 10 to 20 years and seeing its orbital distance shrink.

4. Mutually inclined planets: In the solar system, the planetary orbits are lined up with one another. We have seen that exoplanetary orbits are not necessarily aligned with the rotation of their host star, but less is known about whether they are aligned with one another. The Gaia mission should tell us more about this important "architectural" aspect of planetary systems.

5. Young stars with planets: We know next to nothing about planets around young stars because young stars have inconvenient properties for planet searches. Gaia may help with this problem, too, as will transit surveys of the future and a new telescope called ALMA—the Atacama Large Millimeter/submillimeter Array—that can make images of protoplanetary disks with much higher fidelity than anything that came before.

- It is remarkable that we can learn so much, and might one day learn even more, simply by monitoring the brightness and color of a point of light and applying our knowledge of physics.

Suggested Reading

Sagan, et al, "A Search for Life on Earth from the Galileo Spacecraft."

Seager, "The Future of Spectroscopic Life Detection on Exoplanets."

Seager, ed., *Exoplanets*, chap. 19.

Questions to Consider

1. If there were life beneath an exoplanet's surface or in the depths of an ocean, as opposed to on the surface, would there be any way to detect it through telescopic observations?

2. Search the web (and your favorite science publications) for any mention of the future exoplanetary discoveries listed at the end of this lecture.

Bibliography

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Internet Resources

ESA Science & Technology. http://sci.esa.int/gaia/. The official website for the Gaia mission, a 5-year space mission launched in 2013. It uses a satellite at the second Earth-Sun Lagrange point to measure precise locations of a billion stars and is expected to detect thousands of exoplanets through the astrometric method.

Exoplanets.org. http://exoplanets.org. A reasonably comprehensive catalog of all the properties of known exoplanets, including their sizes, orbits, distances from Earth, etc.

NASA Planetary Fact Sheets. http://nssdc.gsfc.nasa.gov/planetary/planetfact.html. This website presents lots of basic data for the planets in the solar system.

Open Exoplanet Catalogue. http://www.openexoplanetcatalogue.com. Other catalogs of exoplanet properties can be found on this site. It also includes a link to an iPhone app that provides tools to explore exoplanet properties and receive announcements about new discoveries.

The Extrasolar Planets Encyclopedia. http://exoplanet.eu. Other catalogs of exoplanet properties can be found on this site.